International Journal of Electrical Engineering.
ISSN 0974-2158 Volume 7, Number 3 (2014), pp. 377-389

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Total Harmonic Distortion, Distortion Factor & Crest Factor in Sven Level Cascaded H-Bridge Inverter for Different PWM Control Strategies: A Comparative Study

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Abstract

The Multilevel Inverter (MLI) topology gives the advantages of usage in high power and high voltage application with reduced harmonic distortion without a transformer. Multi carrier PWM techniques are extensions of two level PWM methods; the selected switching technique to control the MLI will also have an effective role on harmonic elimination while generating the ideal output voltage. The most common MLI's are the neutral-point-clamped inverter (NPC), flying capacitor inverter (FC), and cascaded H-bridge inverter (CHB). Different Multi carrier PWM techniques are applied to CHB inverter and the performance of circuit topology is analyzed using Matlab/Simulink. The results show that the superiority of Multi carrier PWM techniques over each other using different modulating signals and different carrier signals by varying switching frequency.

Key Words: Carrier over lapping PWM method, Hybrid carrier based PWM method, Level-Shifted Multicarrier Modulation, Phase-Shifted Multi-carrier Modulation, Sub Harmonic PWM method, Variable Frequency PWM method, Wave level Shift Multi-carrier Modulation.

1. Introduction

Multilevel Pulse Width Modulation (PWM) inverters have been gained importance in high performance power applications without requiring high ratings on individual devices, as static var compensators, drives and active power filters. A multilevel inverter divides the dc rail directly or indirectly, so that the output of the leg can be more than two discrete levels. As both amplitude modulation and pulse width

Paper Code: 14480-IJEE

modulation are used in this, the quality of the output waveform gets improved with low distortion. The advantages of multilevel inverter are good power quality, low switching losses, reduced output dv / dt and high voltage capability. Increasing the number of voltage levels in the inverter increases the power rating. The three main topologies of multilevel inverters are the Diode clamped inverter, Flying capacitor inverter, and the Cascaded H-bridge inverter [1-3]. Among the three types of multilevel inverters, the cascade inverter has the least components for a given number of levels. Cascade multilevel inverters consists of a series of H-bridge cells to synthesize a desired voltage from several separate DC sources (SDCSs) which may be obtained from batteries or fuel cells. All these properties of cascade inverters allow using various pulse width modulation (PWM) strategies to control the inverter accurately [4-8]. Abundant modulation techniques and control paradigms have been developed for multilevel converters such as selective harmonic elimination PWM (SHE-PWM), sinusoidal PWM (SPWM), space vector PWM (SVM), Carrier over lapping PWM method, Hybrid carrier based PWM method, Level-Shifted Multicarrier Modulation, Phase-Shifted Multi-carrier Modulation, Variable Frequency PWM method, Wave level Shift Multi-carrier Modulation and Evolutionary algorithms. The modulation methods used in multilevel inverters can be classified according to switching frequencies and type of modulating signal used [16]. The classification of control strategies is shown in fig 1.

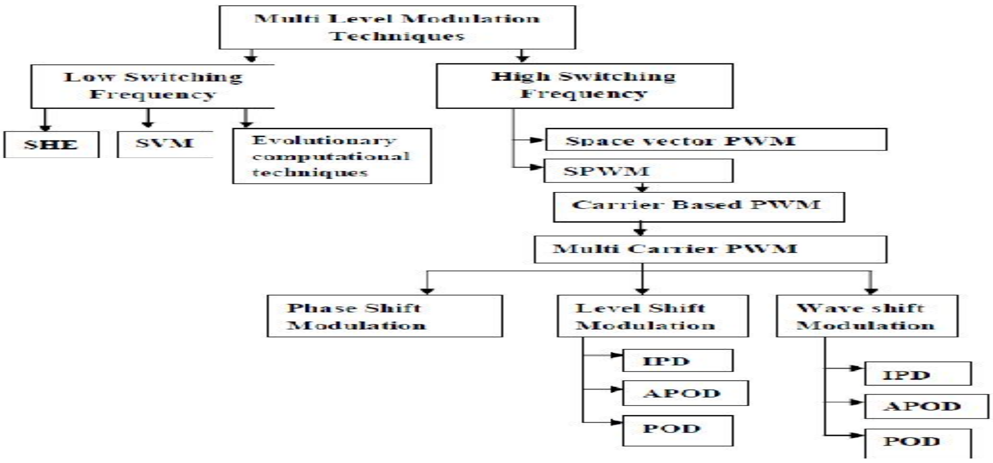


Figure 1. Classification of PWM control strategies

The main advantages of PWM inverters in comparison to square-wave inverters are

- Control over output voltage magnitude
- Reduction in magnitudes of unwanted harmonic voltages
- Improved power factor with unity displacement factor. Lowest order harmonic elimination is possible by proper choice of the number of pulses per half cycle.

2. Multi Carrier PWM Techniques

Multi Carrier based PWM methods have more than one carrier that can be triangular wave or saw tooth waves and so on. The modulating / reference wave of multilevel carrier based PWM strategies can be sinusoidal or trapezoidal.

Carrere considered different methods of disposing the many carrier bands required in multilevel PWM.[2]

Four alternative carrier PWM strategies with differing phase relationships for a multilevel inverter [12] are as follows:

1. In-phase disposition (IPD) or Phase Disposition (PD), where all the carriers are in phase;
2. Phase opposition disposition (POD), where the carriers above the zero reference are in phase, but shifted by 1800 from those carriers below the zero reference;
3. Alternative phase opposition disposition (APOD), where each carrier band is shifted by 1800 from the adjacent bands;
4. Phase Disposition (PD), all the carriers are phase shifted by 2π/(N-1) radians. PD strategy is used most frequently because it produces minimum harmonic distortion for the line–to– line output voltage [9], [10], [11].

A. Phase-Shifted Multi-carrier Modulation (PSHM)

In this type of technique MLI with m voltage levels requires (m – 1) triangular carriers. In the phase-shifted multi-carrier modulation, all the triangular carriers have the same frequency and the same peak-to-peak amplitude, but there is a phase shift between any two adjacent carrier waves, given by: φsh = 360°/ (m-1), [13], [15]

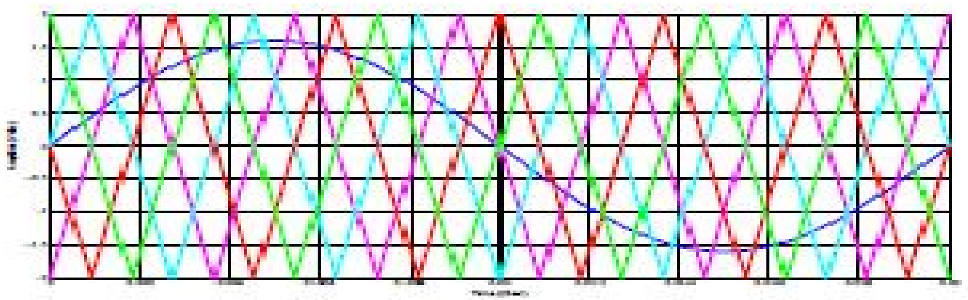


Figure 2. Modulating and carrier waveforms for PSPWM strategy

B. Level-Shifted Multicarrier Modulation (LSHM)

In this type of technique a m-level MLDCL using level-shifted multicarrier modulation scheme, (m – 1) triangular carriers are required, all having the same frequency and amplitude [13]. The (m – 1) triangular carriers are vertically disposed.[15] The amplitude modulation index is defined as

$$M_a = \frac{V_m}{V_c}(m-1)$$

Where

Vm is the peak amplitude of the modulating wave

Vcr is the peak amplitude of each carrier wave

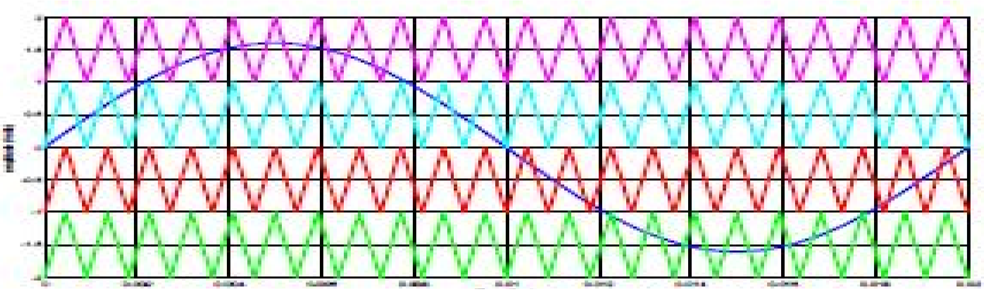


Figure 3. Modulating and carrier waveforms for IPDPWM strategy in Level Shift PWM Technique.

There are three schemes for level shift multi-carrier modulation listed as follows: [16]
(i) *In-phase disposition* (IPD), where all carriers are in phase.
(ii) Alternative phase opposite disposition (APOD), where all carriers are alternatively in opposite disposition.
(iii) Phase opposite disposition (POD), where all carriers above the zero reference are in phase but in opposition with those below the zero reference.

C. Wave level Shift Multi-carrier Modulation (WSHM)

This modulation technique is a combination of phase shift multi-carrier and level-shifted multi-carrier modulation (in-phase disposition (IPD)) schemes and provides small phase displacement to all carriers with each other. For m level, (m – 1) triangular carriers are required.[13] In the carrier wave all the triangles have the same frequency, same peak to peak amplitude and are vertically disposed, but there is a phase shift between any two disposed carrier waves as in

$$\varphi sh = 360°/ 4(m-1)$$

The amplitude modulation index is defined

$$ma = Vm/Vcr(m-1)$$

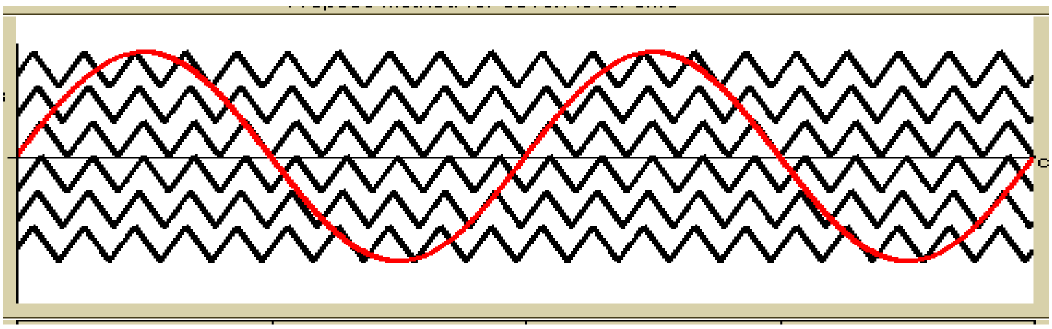


Figure 4. Modulating and carrier waveforms for IPDPWM strategy in Waveshift PWM Technique.

D. Sub Harmonic PWM method

In SHPWM technique all the carriers are in Phase, for an m-level inverter, (m-1) carriers with the same frequency Fc and same peak-to-peak amplitude Ac are used. The reference waveform has amplitude Am and frequency Fm and it is centered about the zero level. The reference wave is continuously compared with each of the carrier signal. If the amplitude of reference wave is more than the carrier then the on pulse is generated and devices correspond to that carrier will ON, otherwise the devices will OFF. [14]

The frequency ratio Mf is defined as Mf=Fc/Fm.

The amplitude modulation index Ma is defined for this method as Ma=2*Am/(m-1)*Ac

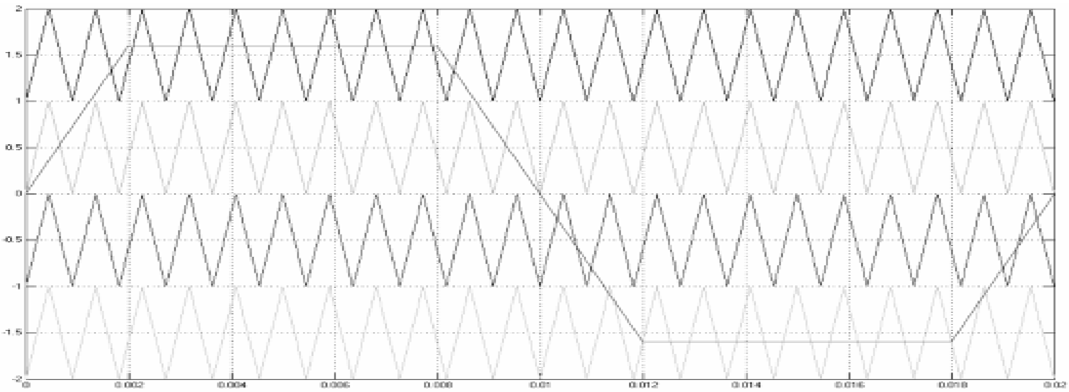


Figure 5. Multi carrier arrangement for SHPWM method

E. Variable Frequency PWM method

The number of switching for upper and lower devices of chosen MLI is much more than that of intermediate switches in SHPWM using constant frequency carriers. In order to equalize the number of switching for all the switches, Variable frequency PWM strategy is used as illustrated in below fig. in which the carrier frequency of the intermediate switches is properly increased to balance the number of switching for all the switches. [14]

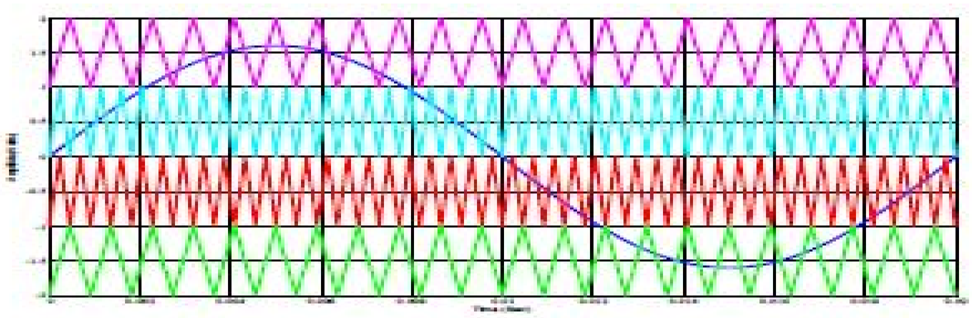


Figure 6. Modulating and carrier waveforms for VFPWM strategy

F. Carrier over lapping PWM method

The principle of COPWM 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. 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 signals. The vertical offset of carriers for chosen five level inverter can be as illustrated in below Figure. It can be seen that the four carriers are overlapped with other and the reference trapezoidal wave is placed at the middle of the four carriers.[15], [16]

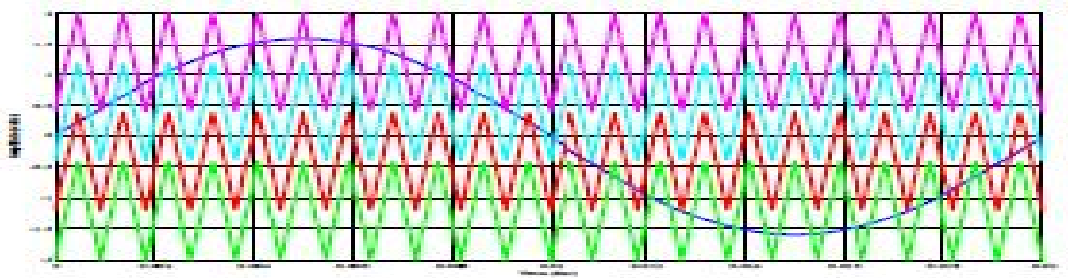


Figure 7. Modulating and carrier waveforms for COPWM strategy

G. Hybrid carrier based PWM method:

This technique, as mentioned earlier combines the previously presented ones (disposition) and the well known Phase Shifted multi carrier technique. As the level of the converter increases the more triangular waves increases and phase shifted accordingly. The carriers above the zero have the same peak-to-peak value and same frequency Fc. However there is a phase of 180 between them for 5 level and for 7 level the phase shift is 120 and for 9 level the phase shift is 90 degrees. [16]

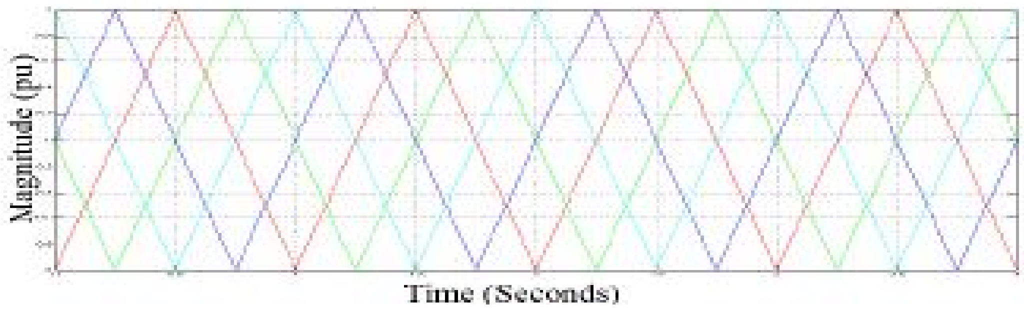
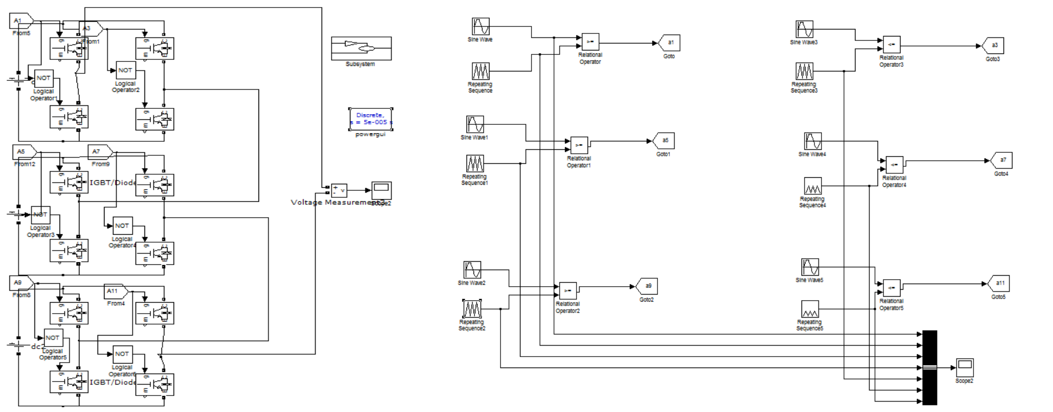


Figure 8. Multi carrier arrangement for Hybrid PWM

3. Simulation Results

Simulation studies are performed by using MATLABSIMULINK to verify the proposed PWM strategies for chosen single phase cascaded H-Bridge seven level inverter for various values of ma ranging from 0.4 – 1 and corresponding %THD values are measured using FFT block and they are shown in Table 2, and Table 5 &6 shows the V_{RMS} & V_{PEAK} of fundamental of MLI's output for the same modulation indices. Fig's.10 – 16 shows the simulated output voltage of chosen CHBMLI and the corresponding FFT plots with different PWM strategies but only for one sample value of MI=1. Fig. 9(a) shows the seven level circuit diagram and Fig 9(a). shows the circuit of a PDPWM control strategy from Table 1 shows that PDPWM gives better THD% when compared with other PWM strategies for 9, 11 & 15 level CHBMLI, therefore the above discussed strategies is been simulated with respective of PDPWM. Table 3 & 4 shows the results of Crest Factor and Distortion Factor of CHBMLI for various PWM techniques for different modulation Index. Fig's 17-21 shows the graphs of calculated THD%, V_{PEAK}, V_{RMS}, CF, DF for various MI. Distortion Factor is calculated for selected Harmonics numbers i.e from 2 to 19 based up on the PWM technique.



(a) (b)

Figure 9. (a) Seven level CHBMLI, (b) control circuit for generating gate control signals using LSHPWM in IPD Scheme.

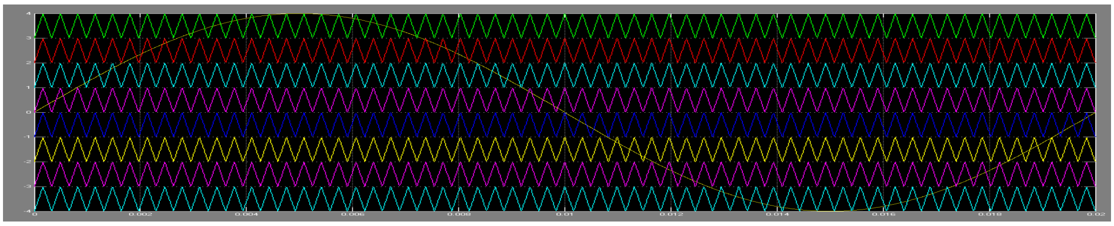
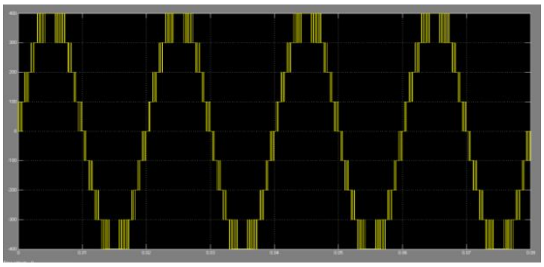
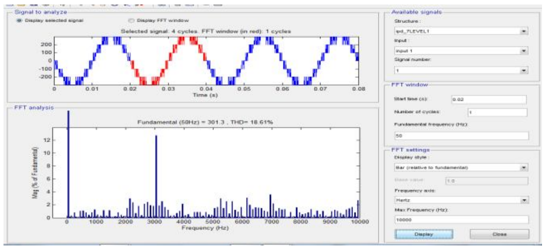
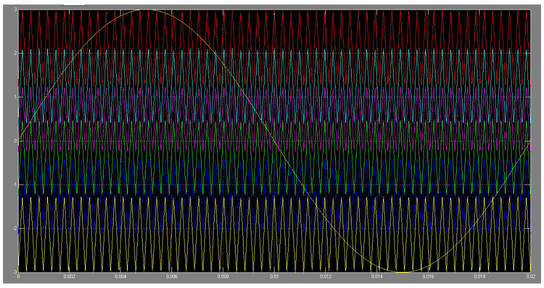
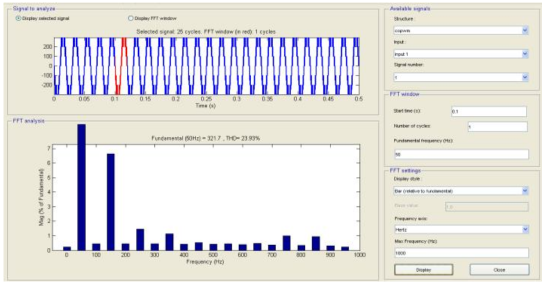


Figure 10. Generating gate signals using PD scheme in LSHPWM

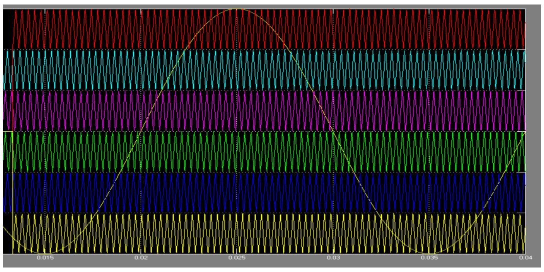
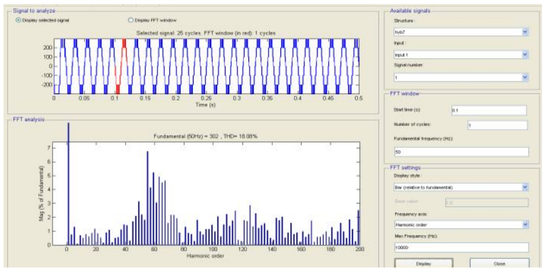
(a) (b)

Figure 11. (a) o/p phase voltage of 9-level CHBMLI using Level shift IPD scheme, (b) THD % of PD in Level Shift PWM

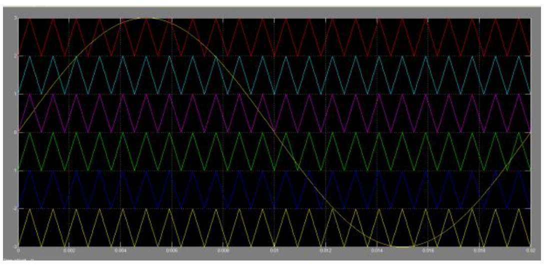
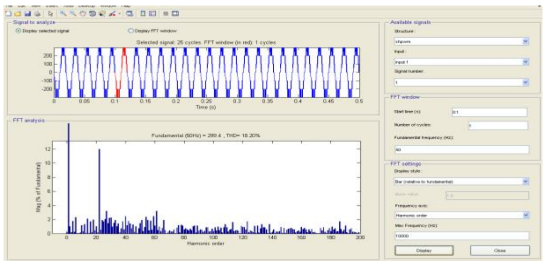
(a) (b)

Figure 12. (a) Generating gate signals using Carrier Overlapping PWM. (b) THD % of Carrier Overlapping PWM

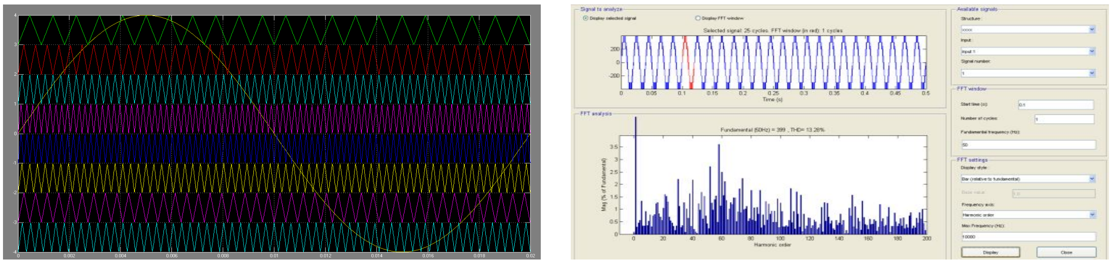
(a) (b)

Figure 13. (a)Generating gate signals using HYBRID PWM, (b) THD % Hybrid PWM

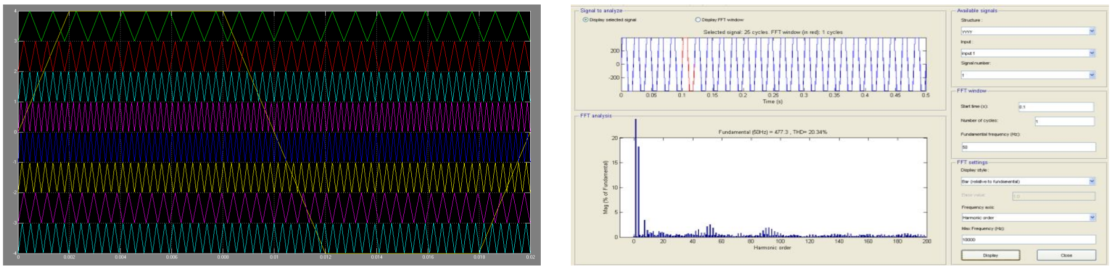
(a) (b)

Figure14. (a) Generating gate signals using Sub Harmonic PWM, (b) THD % of SHPWM



(a) **(b)**

Figure 15. (a) Generating gate signals using Variable Frequency PWM, (b) THD % of VFPWM



(a) **(b)**

Figure 16. (a) Generating gate signals using VFPWM taking Trapezoidal as modulating signal, (b) THD% of VFPWM Trapezoidal

Table 1: Comparison of PSHPWM, LSHPWM, WSHPWM for different level using CHBMLI

LEVEL	TECHNIQUE	IPD	POD	APOD
9	*LSHPWM*	13.40	13.49	13.49
	WSHPWM	13.33	13.37	15.82
	PSHPWM	13.86		
11	*LSHPWM*	10.77	10.82	10.93
	WSHPWM	11.40	11.01	11.01
15	*LSHPWM*	11.00	x	x
	WSHPWM	13.63	x	x

Table: 2 THD% of output voltage of chosen CHMLI for various values of MI and for various PWM's

MI	THD% (for different PWM Strategies & diff Modulation Indices)				
	LSHPWM_PD	COPWM	HYBRIDPWM	VFPWM	SUBHARMONICPWM
1	18.6	23.93	18.23	18.34	18.20
0.8	24.5	30.22	24.46	24.11	23.30
0.6	34.5	43.86	33.62	32.81	32.43
0.4	43.3	61.84	43.27	43.46	42.14

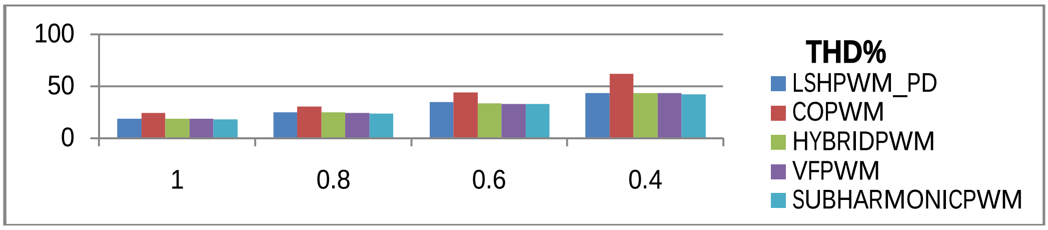


Figure 17. THD% of output voltage of chosen CHMLI for various values of MI and for various PWM's

Table :3 CF of output voltage of chosen CHMLI for various values of MI and for various PWM's.

MI	CREST FACTOR (for different PWM Strategies & diff Modulation Indices)				
	LSHPWM_PD	COPWM	HYBRIDPWM	VFPWM	SUBHARMONICPWM
1	1.4138	1.4140	1.4144	1.4140	1.4142
0.8	1.4142	1.4142	1.4138	1.4147	1.4132
0.6	1.4136	1.4143	1.4140	1.4137	1.4130
0.4	1.4152	1.4148	1.4147	1.4141	1.4144

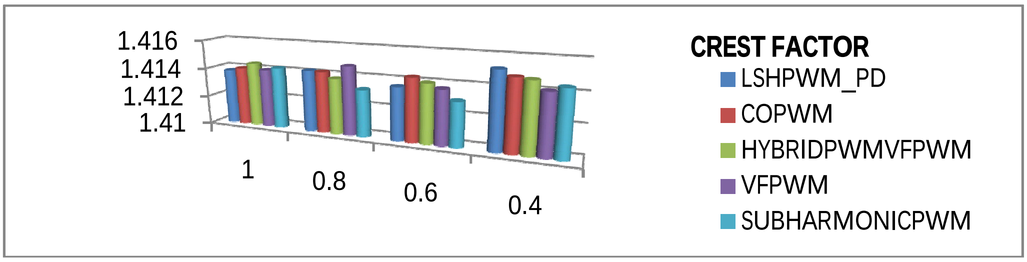


Figure 18. CF of output voltage of chosen CHMLI for various values of MI and for various PWM's

Table:4 : DF of output voltage of chosen CHMLI for various values of MI and for various PWM's

MI	DISTORTION FACTOR (for different PWM Strategies & diff Modulation Indices)				
	LSHPWM_PD	COPWM	HYBRIDPWM	VFPWM	SUBHARMONICPWM
1	0.001158	0.008420	0.001572	0.003443	0.005096
0.8	0.001708	0.004571	0.001946	0.002859	0.002632
0.6	0.0060113	0.002188	0.004571	0.002545	0.004101
0.4	0.003383	0.002354	0.003672	0.001266	0.004311

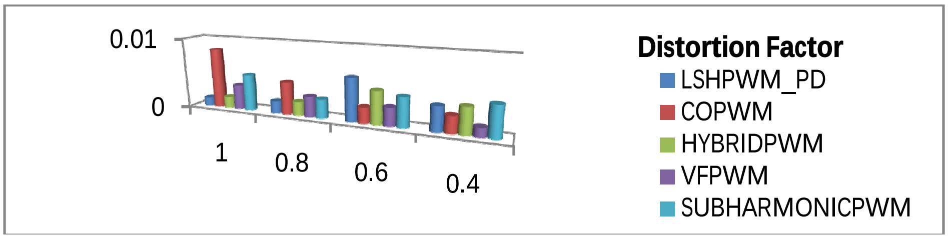


Figure 19. DF of output voltage of chosen CHMLI for various values of MI and for various PWM's

Table:5 Vrms of output voltage of chosen CHMLI for various values of MI and for various PWM's

MI	VRMS (for different PWM Strategies & diff Modulation Indices)				
	LSHPWM_PD	COPWM	HYBRIDPWM	VFPWM	SUBHARMONICPWM
1	213.1	227.5	213.3	213	211.7
0.8	168	196	168.4	170.7	169.3
0.6	125.7	150.6	125.6	127.6	128.2
0.4	85.5	102.7	85.6	84.43	98.91

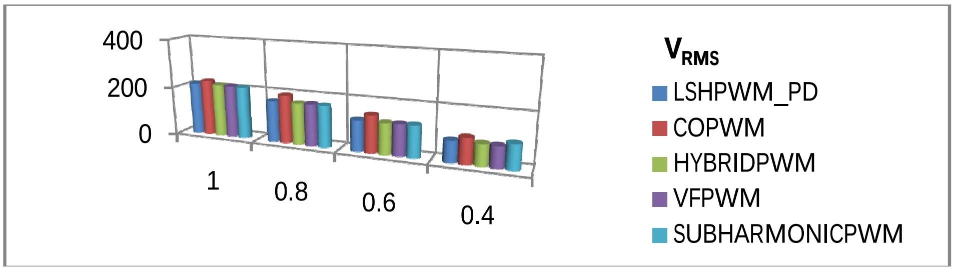


Figure 20. Vrms of output voltage of chosen CHMLI for various values of MI and for various PWM's

Table: 6 Vpeak of output voltage of chosen CHMLI for various values of MI and for various PWM's

	V Peak (for different PWM Strategies & diff Modulation Indices)				
MI	LSHPWM_PD	COPWM	HYBRIDPWM	VFPWM	SUBHARMONICPWM
1	301.3	321.7	301.7	301.2	299.4
0.8	237.6	277.2	238.1	241.5	239.4
0.6	177.7	213	177.6	180.4	181.3
0.4	121	145.3	121.1	119.4	139.9

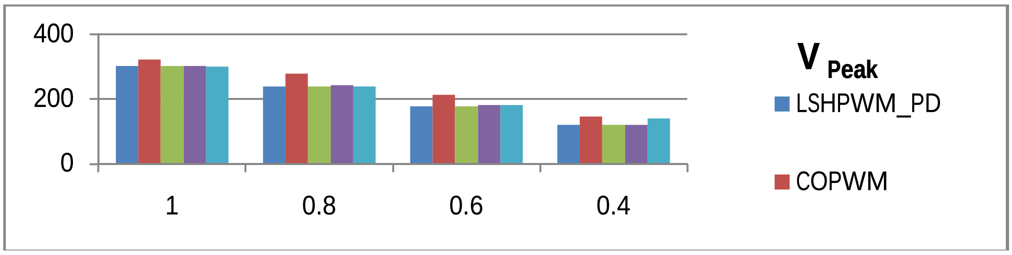


Figure 21. VPeak of output voltage of chosen CHMLI for various values of MI and for various PWM's

4. Conclusion

This paper presents the simulation results of single phase seven level Cascade H-bridge multilevel inverter with resistive load with various modulating strategies are obtained through MATLAB/SIMULINK, various performance measures like THD, V_{RMS}, V_{PEAK}, Crest factor, Distortion Factor were obtained and tabulated. It is observed from "Table.1" that PDPWM method provides output with relatively low distortion when compared with different levels of single phase CHBMLI.

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