CARRIER BASED PWM TECHNIQUE FOR HARMONIC REDUCTION IN CASCADED MULTILEVEL INVERTERS

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ABSTRACT

Cascaded multilevel inverters have received more attention due to their ability to generate high quality output waveforms with low switching frequency. This paper deals with a novel analysis of a carrier based PWM method for cascaded multilevel inverters. Its effect on the harmonic spectrum is analysed. The voltage source inverters are modelled and the same is used for simulation studies. The effectiveness of the proposed control technique is verified by the simulation results. The test results verify the effectiveness of the proposed strategy in terms of computational efficiency as well as the capability of the inverter to produce very low distorted voltage with low switching losses.

Keywords: *Carrier Based PWM technique, Cascaded Multilevel Inverter, Matlab Simulink, Total Harmonic Distortion.*

1. INTRODUCTION

Power electronic converter includes multilevel inverter. It is very popular and synthesizes from several levels of dc input voltages, a desired output voltage. A nearly sinusoidal voltage waveform can be obtained if many dc sources are used. The multilevel inverter compared to the hard switched two level pulse width modulation inverter, has several advantages such as high efficiency, low electromagnetic interference and its capabilities to operate at high voltage with lower dv/dt per switching [1]-[4].

To synthesize the multilevel output ac voltage using different levels of dc inputs, the semiconductor devices must be switched on and off such that the desired fundamental is obtained with minimum harmonic distortion. Selective harmonic elimination (SHE) is a commonly employed switching technique in which at the fundamental frequency the transcendental equations characterizing harmonics are solved to compute the switching angles [2]-[3]. Due to the fact that they are highly nonlinear in nature and may produce simple, multiple or even no solutions for a particular value of modulation index, the SHE equations are difficult to be solved. A big task is how to get all possible solution sets where they exist using simple and less computationally complex method. Once these solution sets are obtained, the solutions having least THD are chosen. Iterative numerical techniques have been implemented to solve the SHE equations producing only one solution set. Even for this, a proper initial guess and starting value of modulation index for which solutions exist are required [4]-[6]. The theory of resultants of polynomials and the theory of symmetric polynomials has been suggested to solve the polynomial equations obtained from the transcendental equations [7]-[8]. For several H-bridges connected in series, the polynomial order becomes very high. So the computations of the solutions of these polynomials becomes complex. Optimization technique based on Genetic Algorithm was proposed for computing switching angles for 7 level inverter in [9].

Cascaded multilevel inverter implemented using a single DC power source and capacitors is given by [10]. A new approach to medium voltage variable frequency static AC motor drives offers improvements in power quality as in [11]. The elimination of lower order harmonics in multilevel inverters using genetic algorithm is given by [12]. The harmonic mitigation in various levels of multilevel inverter with different loads is given by [13]. This paper investigates on improved performance of PWM

strategy for controlling the harmonics of output voltage of chosen CMLI employing carrier based PWM methods.

2. CASCADED MULTI LEVEL INVERTER

The cascaded multilevel inverter requires least number of components when compared to diode clamped and flying capacitors type of multilevel inverters. It has its own importance in the family of multilevel and multipulse inverters. As compared to a multipulse inverter, it does not require a specially designed transformer. It has modular structure with simple switching strategy and occupies less space [1],[3].

The cascaded multilevel inverter consists of many H-bridge inverter units. Each H-bridge unit has a separate dc source and is connected in series or cascade as shown in Fig.1. Each H-bridge can produce three different voltage levels namely $+V_{dc}$, 0 and $-V_{dc}$ by connecting the dc source to ac output side by different combinations of the four switches namely S_1, S_2, S_3 and S_4. The ac output of each H-bridge is connected in series such that the synthesized output voltage waveform is the sum of all the individual H-bridge outputs. A nearly sinusoidal output voltage waveform can be synthesized by connecting sufficient number of H-bridges in cascade and by employing proper modulation scheme. The number of output phase voltage levels is 2s+1 where s is the number of H-bridges used per phase.
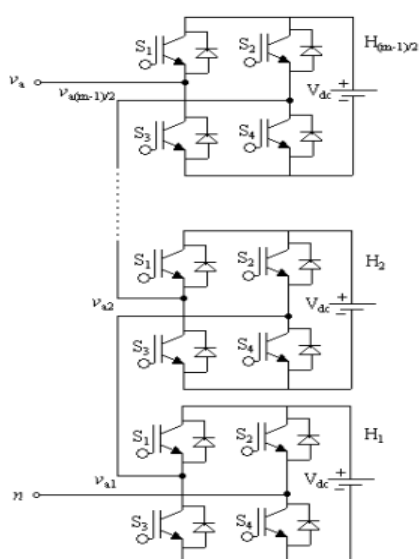
The cascaded (modular) topology has an important feature that it is suitable for high voltage power system applications. The core part of the pulse generation to the inverter is the modulation strategy. It should meet the following advantages which includes voltage balancing and reduced harmonic content. The carrier based PWM technique is chosen here because of its easiness in implementation, low harmonic content and reduction in switching losses. Futher more, the multicarrier PWM is classified as level shifted (vertical arrangement of carriers) and phase shifted (horizontal arrangement of carriers).

Fig.2 shows a five level cascaded H-bridge multilevel inverter. An m level cascaded H-bridge multilevel inverter requires 2(m-1) switching devices where m is the number of the output voltage level.
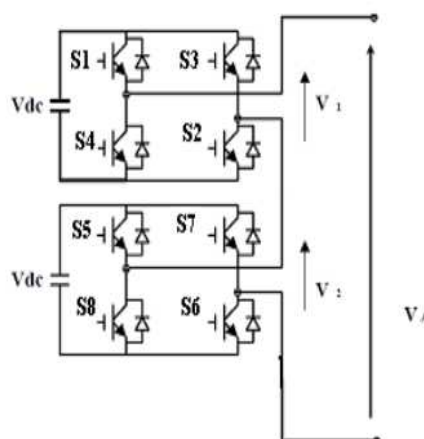

Fig.2. Five Level Cascaded Multilevel Inverter

The switch states and voltage levels of five level cascaded inverter is shown in Table 1.

Table.1. Switch States And Voltage Levels Of Five Level Cascaded Inverter

S1	S2	S3	S4	S5	S6	S7	S8	OUTPUT VOLTAGES
0	0	0	0	0	0	0	0	0
1	0	0	1	0	0	0	0	V1
0	0	0	0	1	0	0	1	V2
0	1	1	0	0	0	0	0	-V1
0	0	0	0	0	1	1	0	-V2

Fig.1. Configuration Of Single Phase Cascaded Multilevel Inverter

The five level cascaded multilevel inverter has less number of components. There is no need of extra diodes and capacitors. It allows scalable, modularized circuit layout and packaging.

Fig.3 shows a seven level cascaded H-bridge multilevel inverter. It requires 12 switching devices and three dc sources.
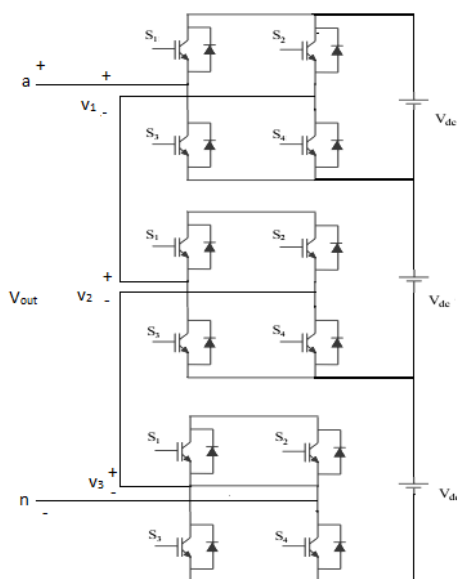

Fig.3. Seven Level Cascaded Multilevel Inverter

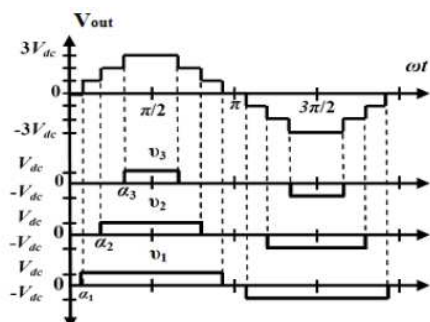The output voltage of cascaded H-bridge seven level inverter is shown in Fig.4.

Fig.4. Output Voltage Of Cascaded H-Bridge Seven Level Inverter

3. MODULATION STRATEGIES FOR MULTILEVEL INVERTER

For multilevel power conversion applications a number of modulation strategies are used. They are classified into three categories namely: (i) multistep, staircase or fundamental frequency switching modulation strategies; (ii) space vector PWM strategies; (iii) carrier based PWM strategies. Carrier based strategies includes single carrier and multicarrier strategies. Different multilevel topologies lend to different multicarrier based PWM schemes. The multicarrier PWM schemes can be categorized into two groups: Carrier disposition methods where the reference waveform is sampled through a number of carrier waveforms displaced by contiguous increments of the waveform amplitude and the phase shift PWM methods where multiple carriers are shifted accordingly. The carrier based PWM methods have more than one carrier which can be saw tooth waves or triangular waves and so on. There are multiple control freedom degree for carrier signals including amplitude, frequency and phase of each carrier and also offsets between the carriers. Multicarrier PWM strategies can also be categorized into unipolar and bipolar types. This paper focuses on the usage of sine and trapezoidal waveforms as modulating reference waves for multilevel carrier based PWM technique for harmonic reduction in cascaded multilevel inverters.

4. CARRIER BASED MODULATION TECHNIQUES

The fundamental frequency switching modulation strategies and the space vector PWM strategies are very complicated. Due to the above limitations, the carrier based PWM strategies are preferred. In Sub Harmonic PWM (SHPWM), all carriers are in phase. In Variable Frequency PWM (VFPWM), all the carriers are in phase, same amplitude but with different frequency. The carrier based modulation schemes for multilevel inverters can be generally classified into two groups. They are phase shifted modulation and level shifted modulation. The phase shifted modulation produces higher THD compared to the level shifted modulation when applied to cascaded H-bridge inverters. An m level multilevel inverter using level shifted multicarrier modulation scheme requires (m-1) triangular carriers, all having the same frequency and amplitude. The (m-1) triangular waves are

vertically disposed such that the bands they occupy are contiguous. For the level shifted multicarrier modulation scheme, there are three alternative pulses with different phase relationships. The three alternative carrier disposition pulse width modulation strategies are:

(1) Alternative phase opposition disposition, where each carrier is phase shifted by 180 degrees from its adjacent carrier.

(2) Phase opposition disposition, where the carriers above the sinusoidal reference zero point are 180 degrees out of phase with those below the zero point.

(3) Phase disposition, where all the carriers are in phase.

In this work, carrier based PWM techniques are employed to Cascaded Multilevel Inverters. The amplitude modulation index is given by m_a .

$$m_a = 2A_m/(m-3)A_c$$

where A_m = Amplitude of reference
A_c = Amplitude of carrier

Also the frequency ratio is given by m_f.

$$m_f = f_c/f_m$$

where f_m = Frequency of reference
f_c = Frequency of carrier

The carrier overlapping PWM (COPWM) strategies utilizes the Control Freedom Degree of vertical offset among carriers. It involves three methods namely: COPWM-A, COPWM-B and COPWM-C. For an 'm' level inverter using carrier overlapping technique, (m-1) carrier with the same frequency f_c and peak to peak amplitude A_c are disposed such that the bands they occupy overlap each other. The overlapping vertical distance between each carrier is $A_c/2$. In this paper both sine and trapezoidal waveforms are used as modulating reference waves.

In the carrier overlapping PWM (COPWM)-A method, the carriers are overlapped with other and the reference wave is placed at the middle of the carriers.

In the carrier overlapping PWM (COPWM)-B method, the carriers are divided equally into two groups according to the positive/negative average levels. In this type, two groups are opposite in phase with each other while keeping in phase within the group.

In the carrier overlapping PWM (COPWM)-C method, the carriers invert their phase in turns from the previous one. It may be identified as PWM with the amplitude overlapped and neighbouring phase interleaved carriers.

5. SIMULATION RESULTS

The cascaded five level inverter and seven level inverter is modelled using the blocks of Matlab simulink. Digital simulation is done and the results are presented here. Simulations are performed for different values of modulation indices with sine and trapezoidal references for various modulation strategies. The corresponding value of %THD is measured using the FFT block. The output voltage is also obtained. The performance measures which are the %THD and V_{RMS} which are obtained are tabulated. The simulation results presented in this work in the form of outputs of the chosen multilevel inverter are compared and evaluated.

Fig.5 shows the carriers for seven level inverter with VFPWM strategy employing sine wave as reference for modulation index 0.8. Fig.6 and Fig.7 shows the corresponding simulated output voltage and FFT spectrum. Table 2 shows the %THD and V_{RMS} comparison for different modulation indices with sine reference of a seven level inverter. From Fig.7, it is observed that seven level inverter with VFPWM strategy employing sine wave as reference produces significant 16th, 18th and 20th harmonic energy. Fig.8 shows the carriers for five level inverter with VFPWM strategy employing trapezoidal wave as reference for modulation index 0.8. Fig.9 and Fig.10 shows the corresponding simulated output voltage and FFT spectrum. Table 3 shows the %THD and V_{RMS} comparison for different modulation indices with trapezoidal reference of a five level inverter. From Fig.10, it is observed that five level inverter with VFPWM strategy employing trapezoidal wave as reference produces significant 3rd and 20th harmonic energy.

Fig.11 shows the carriers for seven level inverter with PDPWM strategy employing sine wave as reference for modulation index 0.8. Fig.12 and Fig.13 shows the corresponding simulated output voltage and FFT spectrum. Table 4 shows the %THD and V_{RMS} comparison for different modulation indices with sine reference of a seven level inverter. From Fig.13, it is observed that seven level inverter with PDPWM strategy employing sine wave as reference produces significant 6th, 8th, 14th and 20th harmonic energy. Fig.14 shows the carriers for five level inverter with PDPWM strategy employing trapezoidal wave as reference for modulation index 0.8. Fig.15 and Fig.16 shows

the corresponding simulated output voltage and FFT spectrum. Table 5 shows the %THD and V_{RMS} comparison for different modulation indices with trapezoidal reference of a five level inverter. From Fig.16, it is observed that five level inverter with PDPWM strategy employing trapezoidal wave as reference produces significant 3rd, 7th, 8th and 20th harmonic energy.

Fig.17 shows the carriers for seven level inverter with COPWM-A strategy employing sine wave as reference for modulation index 0.8. Fig.18 and Fig.19 shows the corresponding simulated output voltage and FFT spectrum. Table 6 shows the %THD and V_{RMS} comparison for different modulation indices with sine reference of a seven level inverter. From Fig.19, it is observed that seven level inverter with COPWM-A strategy employing sine wave as reference produces significant 20th harmonic energy. Fig.20 shows the carriers for five level inverter with COPWM-A strategy employing trapezoidal wave as reference for modulation index 0.8. Fig.21 and Fig.22 shows the corresponding simulated output voltage and FFT spectrum. Table 7 shows the %THD and V_{RMS} comparison for different modulation indices with trapezoidal reference of a five level inverter. From Fig.22, it is observed that five level inverter with COPWM-A strategy employing trapezoidal wave as reference produces significant 3rd, 5th, 18th and 20th harmonic energy.
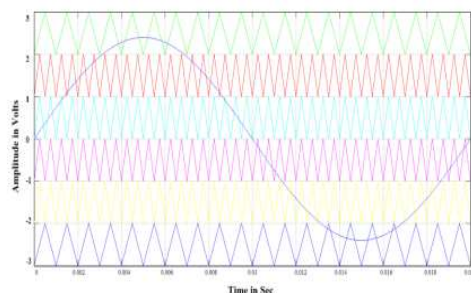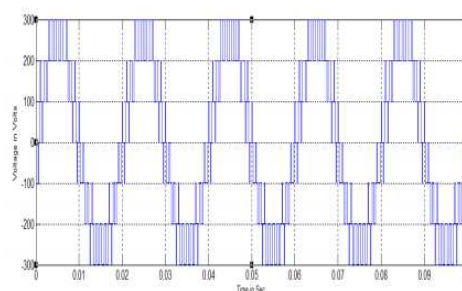
Fig.6. Output Voltage Generated By Vfpwm Strategy With Sine Reference For A Seven Level Inverter
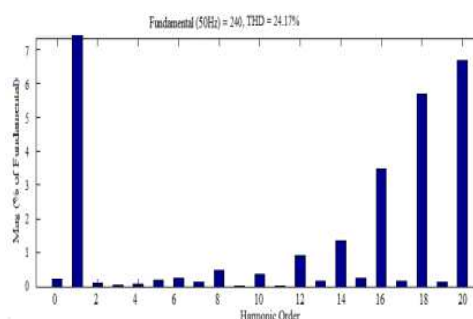

Fig.7. Fft Plot For Output Voltage Of Vfpwm Strategy With Sine Reference For A Seven Level Inverter

Table 2. %Thd And V_{rms} Comparison For Different Modulation Indices With Sine Reference Of A Seven Level Inverter.

MODULATION INDEX	% THD	V_{RMS}
1	18.27	212.2
0.9	22.42	190.8
0.8	24.17	169.7
0.7	25.23	148.2

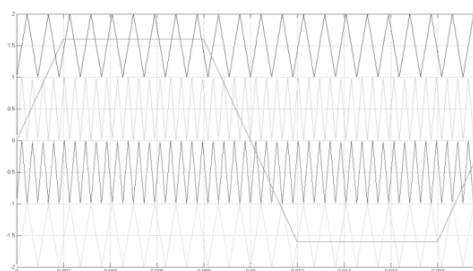*Fig.5. Carrier Arrangement For Vfpwm Strategy With Sine Reference For A Seven Level Inverter*

Fig.8.Carrier Arrangement For Vfpwm Strategy With Trapezoidal Reference For A Five Level Inverter
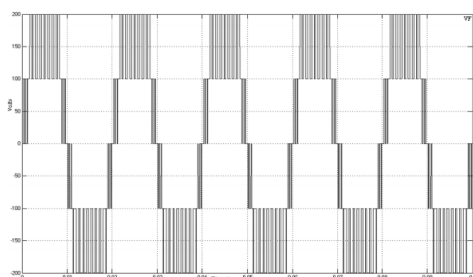

Fig.9. Output Voltage Generated By Vfpwm Strategy With Trapezoidal Reference For A Five Level Inverter
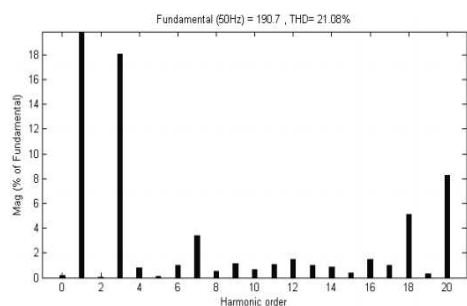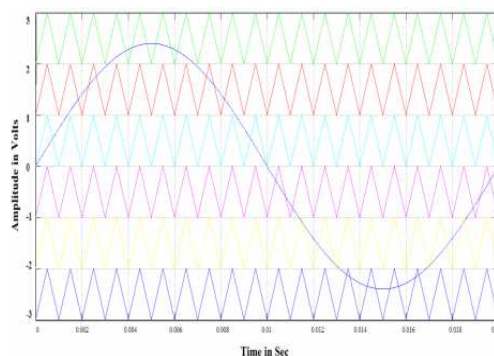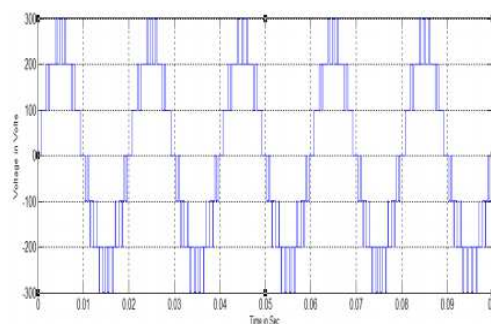

Fig.10. Fft Plot For Output Voltage Of Vfpwm Strategy With Trapezoidal Reference For A Five Level Inverter

Table 3. %Thd And V_{rms} Comparison For Different Modulation Indices With Trapezoidal Reference Of A Five Level Inverter.

MODULATION INDEX	% THD	V_{RMS}
1	19.16	168.4
0.9	19.43	151.5
0.8	21.08	134.8
0.7	21.73	117.8

Fig.11. Carrier Arrangement For Pdpwm Strategy With Sine Reference For A Seven Level Inverter

Fig.12. Output Voltage Generated By Pdpwm Strategy With Sine Reference For A Seven Level Inverter
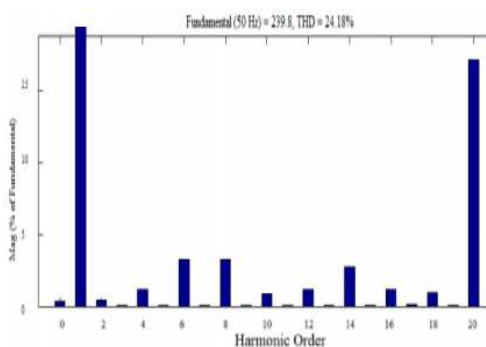

Fig.13. Fft Plot For Output Voltage Of Pdpwm Strategy With Sine Reference For A Seven Level Inverter

Table 4. %Thd And V_{rms} Comparison For Different Modulation Indices With Sine Reference Of A Seven Level Inverter.

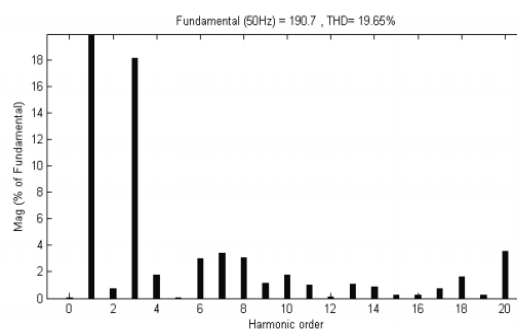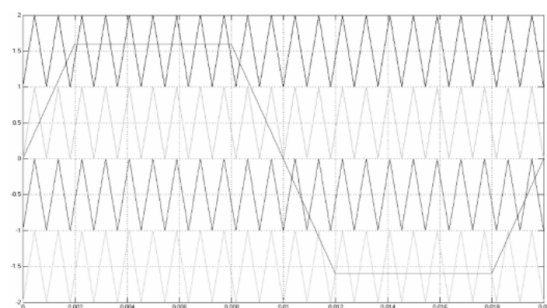| MODULATION INDEX	% THD	V_{RMS}
1	17.82	212.2
0.9	22.49	190.7
0.8	24.18	169.6
0.7	24.91	148.2

Fig.14.Carrier Arrangement For Pdpwm Strategy With Trapezoidal Reference For A Five Level Inverter

Fig.15. Output Voltage Generated By Pdpwm Strategy With Trapezoidal Reference For A Five Level Inverter

Fig.16. Fft Plot For Output Voltage Of Pdpwm Strategy With Trapezoidal Reference For A Five Level Inverter

Table 5. %Thd And V_{rms} Comparison For Different Modulation Indices With Trapezoidal Reference Of A Five Level Inverter.

MODULATION INDEX	% THD	V_{RMS}
1	19.38	168.2
0.9	18.60	151.4
0.8	19.65	134.8
0.7	20.09	118

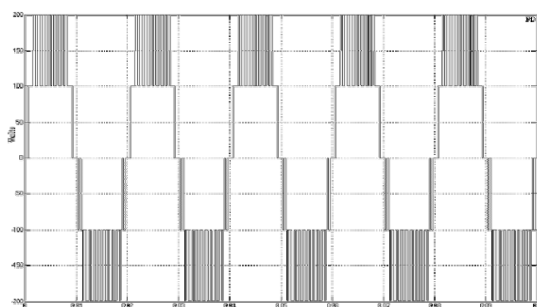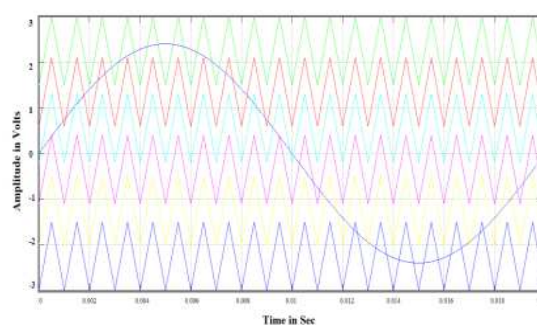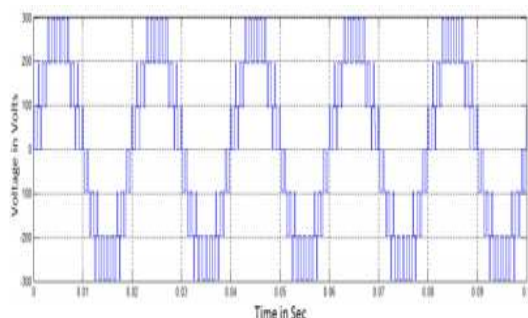*Fig.17. Carrier Arrangement For Copwm-A Strategy With Sine Reference For A Seven Level Inverter*

Fig.18. Output Voltage Generated By Copwm-A Strategy With Sine Reference For A Seven Level Inverter
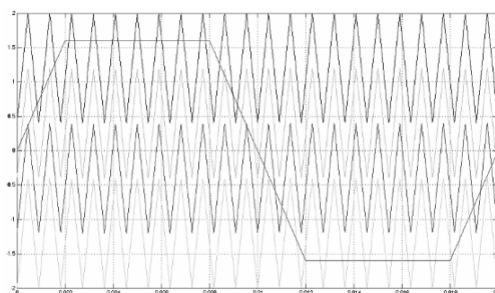

Fig.20. Carrier Arrangement For Copwm-A Strategy With Trapezoidal Reference For A Five Level Inverter
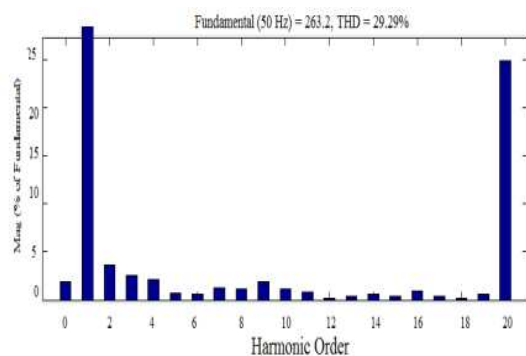

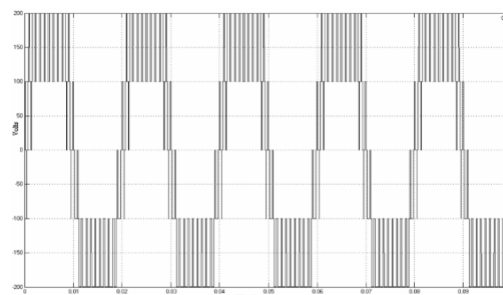*Fig.19. Fft Plot For Output Voltage Of Copwm-A Strategy With Sine Reference For A Seven Level Inverter*

Fig.21. Output Voltage Generated By Copwm-A Strategy With Trapezoidal Reference For A Five Level Inverter

Table 6. %Thd And V_{rms} Comparison For Different Modulation Indices With Sine Reference Of A Seven Level Inverter

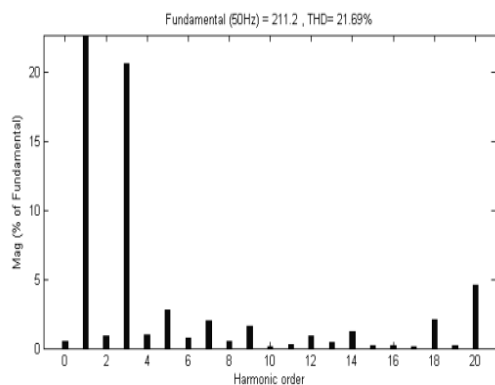| MODULATION INDEX	% THD	V_{RMS}
1	20.75	222.6
0.9	26.36	204.1
0.8	29.29	186.1
0.7	34.48	165

Fig.22. Fft Plot For Output Voltage Of Copwm-A Strategy With Trapezoidal Reference For A Five Level Inverter

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Table 7. %Thd And V_{rms} Comparison For Different Modulation Indices With Trapezoidal Reference Of A Five Level Inverter.

MODULATION INDEX	% THD	V$_{RMS}$
1	24.15	171.1
0.9	22.93	160.4
0.8	21.69	149.3
0.7	20.06	138.1

6. CONCLUSION

In this work, the simulation results of single phase five level inverter and single phase seven level inverter with various modulating strategies employing sine and trapezoidal references are obtained through MATLAB/SIMULINK.. The performance measures such as %THD and V_{RMS} has been analysed and tabulated. For five level inverter employing trapezoidal wave as reference, the PDPWM strategy provides lower %THD than the other methods for moderate modulation index whereas for high modulation index the VFPWM strategy provides better performance. For seven level inverter employing sine wave as reference, the VFPWM strategy provides lower %THD than the other methods for moderate modulation index whereas for high modulation index the PDPWM strategy provides better performance. For both five level inverter employing trapezoidal wave as reference and seven level inverter employing sine wave as reference, the COPWM-A strategy provides better DC utilization.

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