COMPARISON OF CASCADED FIFTEEN LEVEL INVERTER MULTICARRIER SPWM STRATEGIES

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Abstract: This paper puts forward different SPWM control strategies and modulation techniques of fifteen level H bridge multilevel inverter. Two control strategies are presented; the triangular multicarrier SPWM and the saw tooth multicarrier SPWM. For these two control strategies, different modulation techniques such as phase disposition (PD), alternative phase disposition (APD), phase opposition disposition (POD) and alternative phase disposition (APOD) are implemented.
A comparison between the modulation techniques of each control strategy is made. Next, a comparison between the two control strategies.
The subjects of comparison are the output voltage fundamental and the total harmonic distortion (THD).
The obtained simulation results have proved that phase disposition (PD) is the best modulation technique and the saw tooth multicarrier SPWM control starategy is better than the triangular multicarrier SPWM control strategy. Simulations are carried out by PSIM program.

Key words: Modulation index, Sinusoidal Pulse Width Modulation SPWM, Saw Tooth Multicarrier STM SPWM, THD, Triangular Multicarrier TM SPWM ,PD , POD, APOD and APD .

1. Introduction

for several years (approximately 20 years), we are witnessing a renewed interest for the study of multilevel techniques, particularly the multilevel inverters [1].

Over the past two decades, many PWM control strategies of multilevel inverters were studied in order to improve the output signals of these inverters.

Among the control strategies we distinguish three PWM strategies; the SPWM, the SVPWM [2] and the selective harmonic elimination PWM [3-4].

Among the PWM control strategies, the SPWM is the most used to multivel inverters, because of its simplicity and its ease of implementation.

The paper starts with a presentation of the H bridge multilevel inverter followed by a recall of the sinusoidal pulse width modulation SPWM and the four modulation techniques PD, APD, POD and APOD. Definitions of the triangular multicarrier SPWM control strategy and the saw tooth multicarrier SPWM control strategy are given on the ensuing section. Finally a discussion of the simulated results is presented.

2. H bridge multilevel inverter

A cascaded multilevel inverter made up of series connected single full bridge inverter, each with its own isolated DC bus [5-6].

This multilevel inverter can generate almost sinusoidal waveform voltage from several separate DC sources that may be obtained from solar cells, fuel cells, batteries and ultra capacitors [4].

This type of converter does not need any transformer clamping diodes or flying capacitors [5].

Each H bridge N level inverter phase is constituted of $(N-1)/2$ single phase bridge stages.

These bridges are connected in cascade so that the output voltage of H bridge inverter is the sum of output voltages of each single phase bridge.

The number of stages used is related to the inverter levels by the formula:

$$N = (P \times 2) + 1 \qquad (1)$$

N:level number of the output voltage
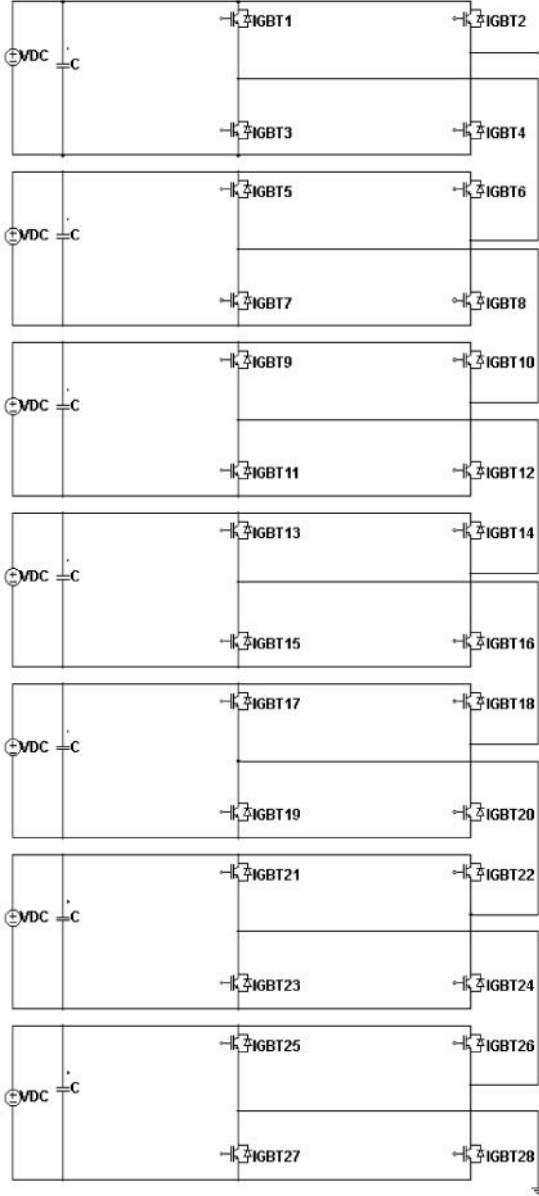P:number of stages per phase.

Fig. 1. Power circuit of a one leg cascaded fifteen level
       inverter

Considering the simplicity and advantages of the circuit, cascade H bridge topology is chosen for the present work.

3. Sinusoidal pulse width modulation SPWM

The generation of SPWM control impulses of an inverter of N voltage levels requires $(N-1)$ carriers

that have the same frequency F_p and the same amplitude A_p [7].

These carriers are compared to the sinusoidal reference signal with an amplitude A_r and a frequency F_r.

For a carrier higher or equal to the reference, the comparison gives 1, and 0 if the carrier is below the reference. At the modulator output the sum of results provided from the comparison is then decoded, and gives the corresponding value to each voltage level [8].

In this paper, two carrier based SPWM techniques are developed as follows [9]:
- Triangular Multicarrier SPWM
- Saw tooth multicarrier SPWM

PWM is characterised by two parameters:

Modulation index: $m = A_r / ((N-1)A_p)$ (2)

Modulation rate: $r = F_p / F_r$ (3)

The phases of carrier signals are rearranged to produce four main disposition techniques known as [10]:

1) Phase Disposition (PD) PWM Strategy

The Principle of PDPWM technique is to use several carriers with single modulating waveform.

In phase disposition all the carriers are in phase and the carriers are disposed so that the bands they occupy are contiguous [11-12].

2)Phase Opposition Disposition (POD) PWM Strategy

With the PODPWM method the carrier waveforms above the zero reference value are in phase. The carrier waveforms below zero are also in phase but are 180 degrees phase shifted from those above zero [11-12].

3)Alternative Phase Opposition Disposition (APOD) PWM Strategy

In case of Alternate Phase Disposition (APOD) modulation[13] each of the carrier waves is phase displaced from each other by 180° alternately [11].

4) Alternative phase Disposition (APD) PWM Strategy

This method requires each of the carrier waves to be phase displaced from each other by 90° alternately.

In our study we use the SPWM control strategy for two kinds of carriers, the triangular multicarrier wave and the saw tooth multicarrier wave. The output voltage waveform is shown for different

modulation techniques through simulations using PSIM for a fifteen level cascaded inverter.

A. Triangular multicarrier SPWM (TM SPWM)

This strategy is based on the comparison of a sine wave reference voltage U_r called modulating signal that has an amplitude A_r and a frequency F_r, to one or more triangle carriers U_p that have the same amplitude $A_p = 2/(N-1)$ and the same frequency F_p.

For *N* level inverter, *(N-1)* level carriers [14] with the same frequency Fc and the same peak amplitude Ac are disposed such as the bands they occupy are contiguous[15]. They are defined as [15] :

$$C_i = A_c((-1)^{f(i)} y_c(w_c, \{) + t - (N/2))$$ (4)

$$i = 1, \ldots\ldots(m-1)$$ (5)

Where y_c is a normalized symmetrical triangular carrier defined as,

$$y_c = (-1)^{\lceil r \rceil}((r.\mathrm{mod}\,2)-1)+1/2$$ (6)

$$r = (w_c t + w)/f = 2f\,f_c$$ (7)
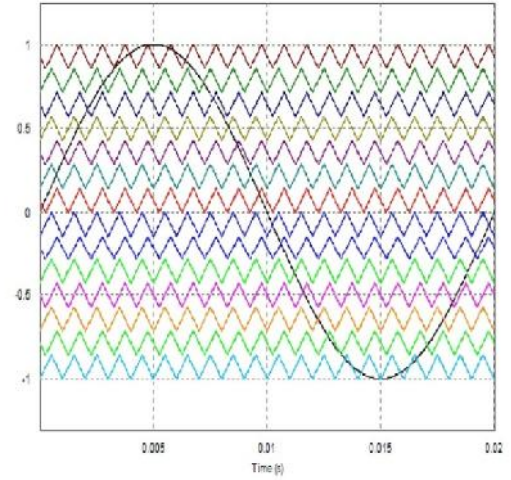
w represents the phase angle of y_c.

y_c is a periodic function with the period [16]:
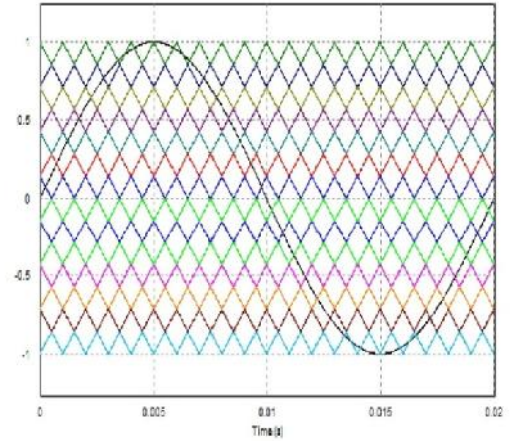
$$T_c = 2\,/\,w_c$$ (8)

The multicarrier modulation techniques phase disposition (PD), alternative phase disposition (APD), phase opposition disposition (POD) and alternative phase disposition (APOD) are implemented using triangular multicarrier signals for a cascaded H bridge fifteen level inverter. They are shown in fig.2
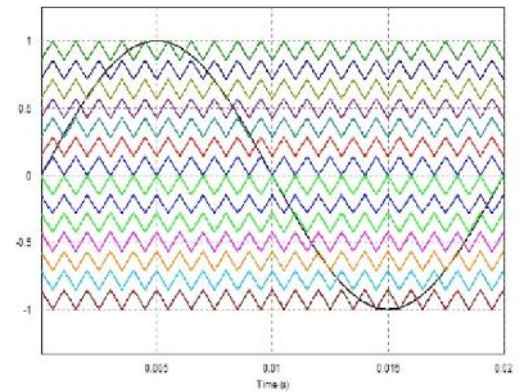
(b)

(c)

(d)

(a)
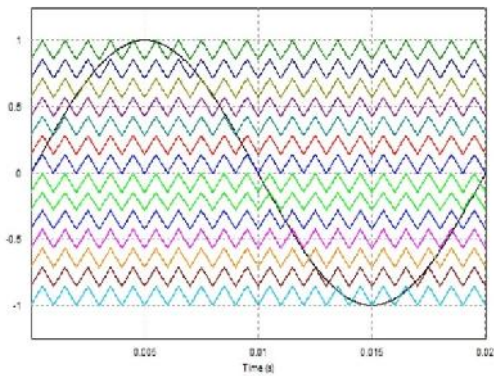
Fig. 2. (a) PD TM SPWM, (b) APD TM SPWM, (c) APOD TM SPWM, (d) POD TM SPWM.

B. Saw tooth multicarrier SPWM (STM SPWM)

The saw tooth wave is a periodic signal and a special case of the triangular wave with the duty cycle of 1 and phase delay of 0.
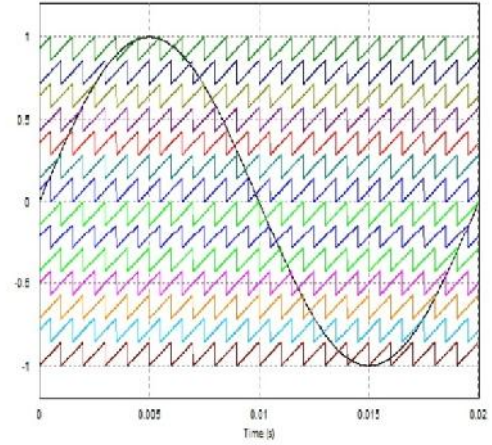
The multicarrier modulation techniques, phase disposition (PD), alternative phase disposition (APD), phase opposition disposition (POD) and alternative phase disposition (APOD) are implemented using saw tooth multicarrier signals for a cascaded H bridge fifteen level inverter. They are shown in fig.3
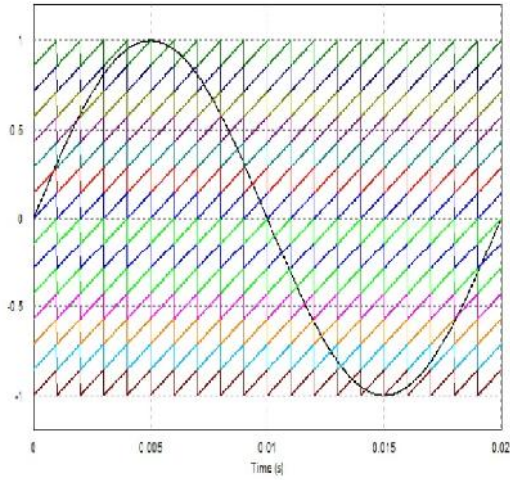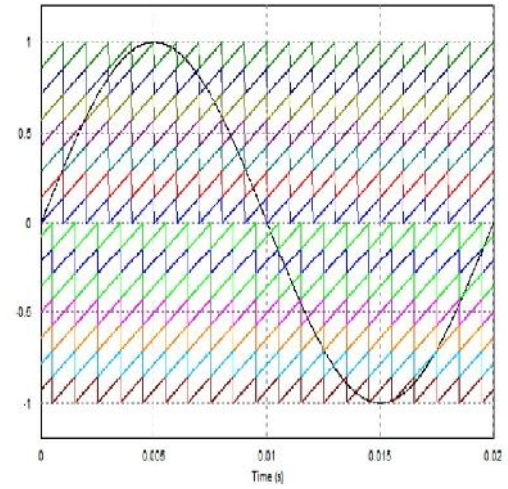

(a)
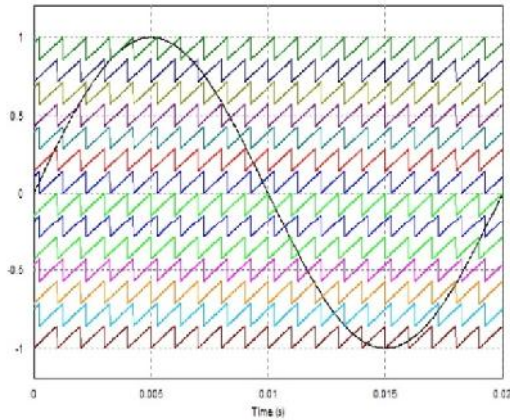
(b)

(c)

(d)

Fig. 3. (a) PD STM SPWM, (b) APD STM SPWM, (c) APOD STM SPWM, (d) POD STM SPWM.

3. Simulation results

To test the feasibility of the SPWM techniques, we use a comparative study based on the fundamental and the THD of output voltage V_{ab} *(V)* for the different modulation techniques, phase disposition (PD), alternative phase disposition (APD), phase opposition disposition (POD) and alternative phase disposition (APOD) using two multicarrier SPWM strategies (TM SPWM and STM SPWM).

H bridge fifteen level inverter simulations with different modulation indexes are carried out by PSIM program.

In order to get the THD level of the waveform, a Fast Fourrier Transform (FFT) of PSIM program is applied to obtain the spectrum of the output phase voltage for the four modulation techniques.

A . Triangular multicarrier SPWM

fig.4, fig.5, fig.6, fig.7 and fig.8 show the phase voltage waveform V_{ab} *(V)* for the cascaded fifteen level inverter using the phase disposition (PD) for the triangular multicarrier SPWM with *m=1* and the harmonic spectra of the four modulation techniques, phase disposition (PD), alternative phase disposition (APD), phase opposition disposition (POD) and alternative phase disposition (APOD).
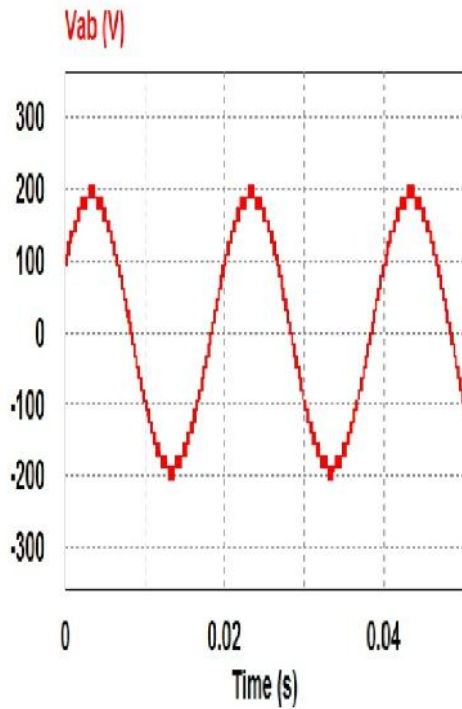

Fig. 5. FFT analysis of Triangular Multi Carrier PDSPWM

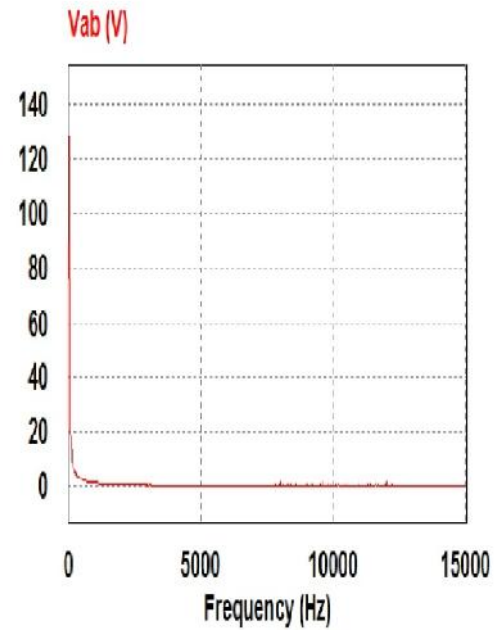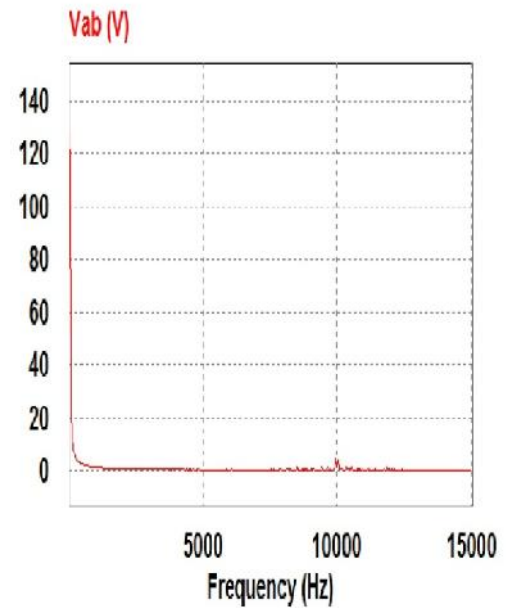Fig. 4. Fifteen level inverter output phase voltage V_{ab} *(V)*

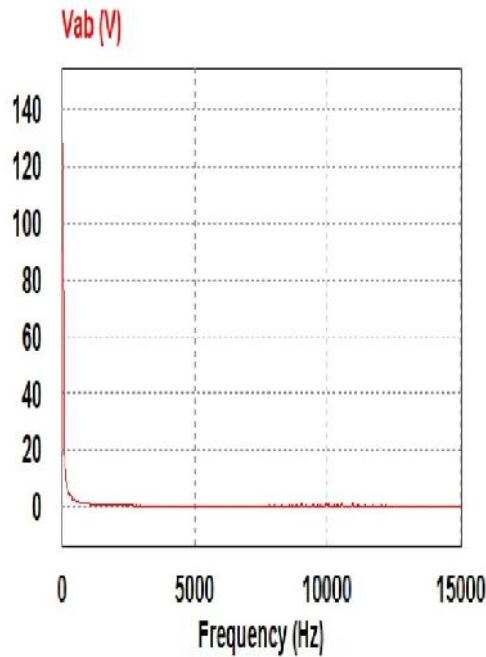Fig. 6. FFT analysis of Triangular Multi Carrier POD SPWM

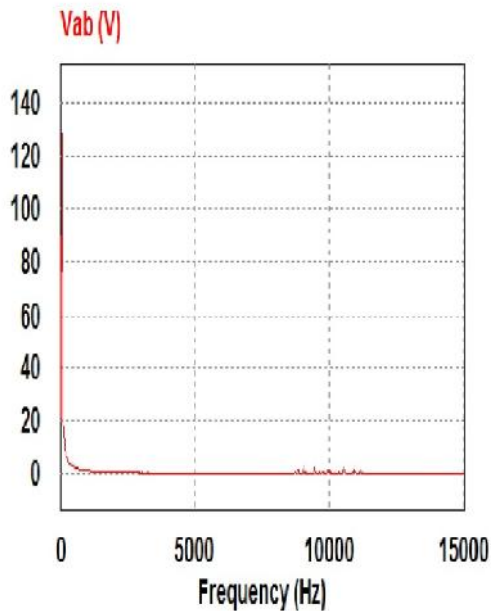Fig. 7. FFT analysis of Triangular Multi Carrier APD SPWM

Fig. 8. FFT analysis of Triangular Multi Carrier APOD SPWM

Table.1 and Table.2 show the total harmonic distortion THD and the fundamental of output voltage V_{ab} *(V)* respectively for the cascade fifteen level inverter with the triangular multicarrier signal for the four SPWM modulation strategies with a switching frequency of 10 *kHz*, for modulation indexes of 0.8, 0.9 and 1.

Table 1: THD of output voltage V_{ab} *(V)* for different SPWM modulation techniques.

m	PD	APD	APOD	POD
0.8	6.14	7.58	8.57	9.59
0.9	5.28	6.68	7.87	7.91
1	4.64	5.32	5.94	6.96

Table 2: fundamental of output voltage V_{ab} *(V)* for different SPWM modulation techniques.

m	PD	APD	APOD	POD
0.8	97.93	97.89	97.97	97.91
0.9	110.04	110.10	110.21	110.10
1	122.46	122.37	122.37	122.35

According to the tables above, we find that the increase of modulation index leads to the increase of the fundamental value and the decrease of THD for the four modulation techniques.

Except for the THD, the decrease is relative for each modulation technique. It is noted that the THD is more reduced for phase disposition (PD) and higher for phase opposition disposition (POD).

From the simulation results (fig.4, fig.5, fig.6, fig.7 and fig.8 and table.1) of the triangular multicarrier SPWM technique :

The harmonic amplitude in relation to the fundamental of 5th harmonic to the 169th harmonic is the same for the modulation techniques, phase disposition (PD), alternative phase disposition (APD), phase opposition disposition (POD) and alternative phase disposition (APOD).

The difference between these four modulation techniques lies in the area included between the 171th harmonic and the 229th harmonic.

Phase disposition (PD):from the 171th to the 229th harmonic, the harmonic amplitude related to the fundamental is less than 1%.

Phase opposition disposition (POD):from the 171th to the 195th harmonic, the harmonic amplitude related to the fundamental is between 1% and 2%. From the 199th to the 201st harmonic, it is equal to 5.31% and 5.13% respectively and from the 205th to the 229th harmonic, it is between 1.5 % and 1 %.

Alternative phase opposition disposition (APOD): from the 171th to the 179th harmonic, the harmonic

amplitude related to the fundamental is less than 1 %. From the 181th to the 217th harmonic, it is between 1 % and 2.37 % and from the 219th to the 229th harmonic, it is less than 1 %.

Alternative phase disposition (APD):from the171st to the 181th harmonic, the harmonic amplitude related to the fundamental is less than 1 %. From the 183th to the 217th harmonic, it varies between 1.25 and 1.65 % and from the 219th to the 229th harmonic, it is less than 1 %.

B. Saw tooth multicarrier SPWM

fig.9, fig.10, fig.11, fig.12 and fig.13 show the phase voltage waveform V_{ab} *(V)* for the cascaded *fifteen* level inverter using the phase disposition (PD) for the saw tooth multicarrier SPWM with *m=1* and the harmonic spectra of the four modulation techniques, phase disposition (PD), alternative phase disposition (APD), phase opposition disposition (POD) and alternative phase disposition (APOD).
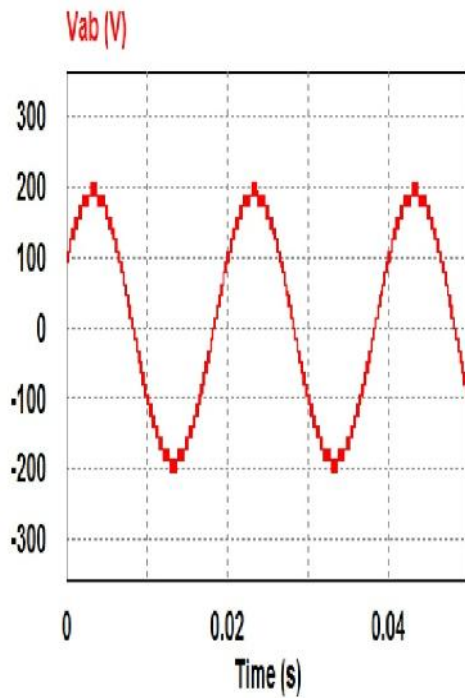

Fig. 10. FFT analysis of saw tooth Multi Carrier APD SPWM

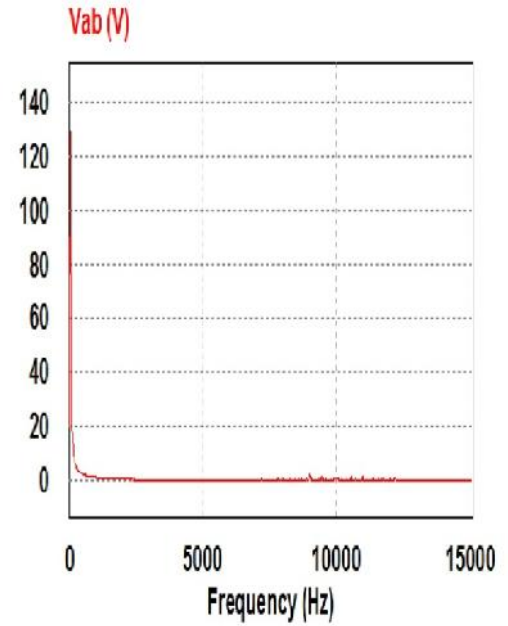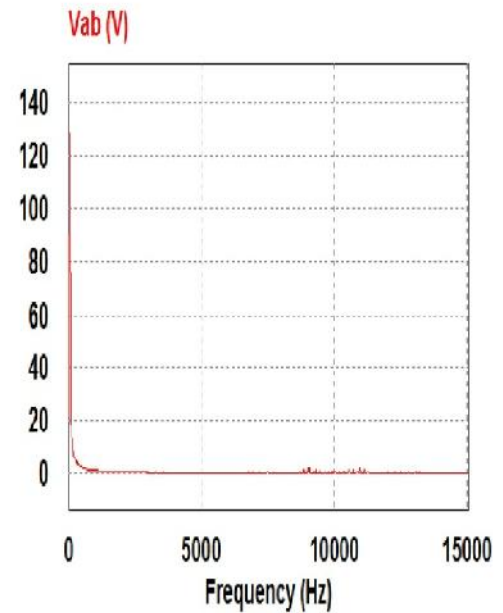Fig. 9. Fifteen level inverter output phase voltage V_{ab} *(V)*

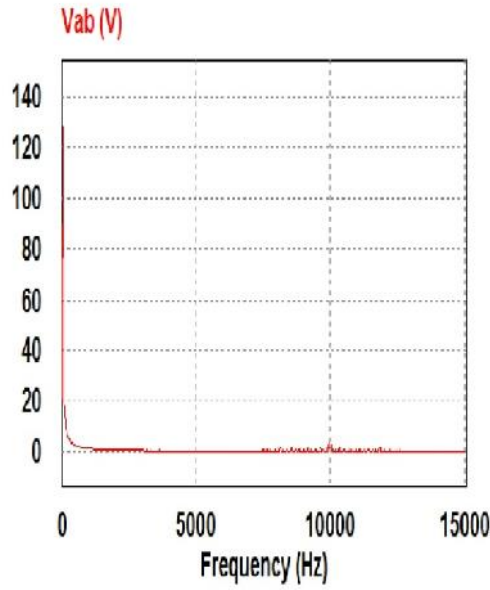Fig. 11. FFT analysis of saw tooth Multi Carrier APOD SPWM

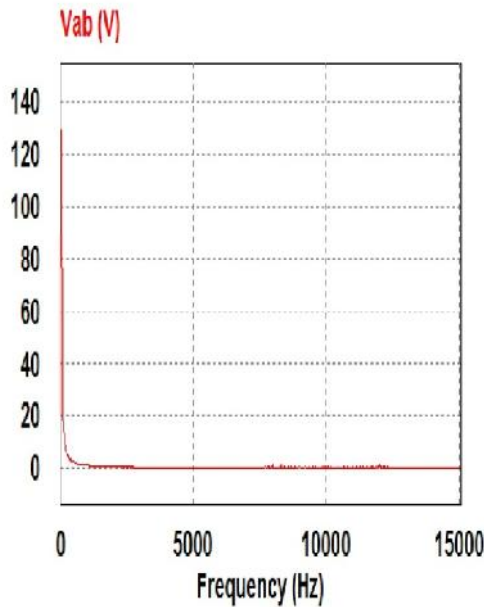Fig. 12. FFT analysis of saw tooth Multi Carrier POD SPWM

Fig. 13. FFT analysis of saw tooth Multi Carrier PD SPWM

Table.3 and Table.4 show the total harmonic distortion THD and the fundamental of output voltage V_{ab} (V) respectively for the cascade fifteen level inverter with the saw tooth multicarrier signal for the four SPWM modulation techniques with a switching frequency of 10 kHz, for modulation indexes of 0.8, 0.9 and 1.

Table 3:THD of output voltage V_{ab} (V) for different SPWM modulation techniques.

m	PD	APD	APOD	POD
0.8	6.12	7.47	8.17	8.89
0.9	5.21	6.98	7.24	7.19
1	4.55	5.29	5.50	6.41

Table 4:fundamental of output voltage V_{ab} (V) for different SPWM modulation techniques.

m	PD	APD	APOD	POD
0.8	97.93	97.9	97.92	97.96
0.9	110.04	110.25	110.21	110.15
1	122.46	122.44	122.41	122.35

According to the tables above, we find that the increase of modulation index leads to the increase of the fundamental value and the decrease of THD for the four modulation techniques. Except for the THD, the decrease is relative for each modulation technique.

It is noted that the THD is more reduced for phase disposition (PD) and higher for phase opposition disposition (POD).

From the simulation results (fig.9, fig.10, fig.11, fig.12 and fig.13 and table.3) of the saw tooth multicarrier SPWM (STM SPWM) technique:

The harmonic amplitude related to the fundamental of the 5th harmonic to the 169th harmonic is the same for the modulation techniques phase disposition (PD), alternative phase disposition (APD), phase opposition disposition (POD) and alternative phase disposition (APOD).

The difference between these four modulation strategies lies in the area included between the 171th and the 229th harmonic.

Phase disposition (PD):From the 171th to the 229th harmonic, the harmonic amplitude related to the fundamental is less than 1 %.

Phase opposition disposition (POD):from the 171th to the 195th harmonic, the harmonic amplitude related to the fundamental is between 1 % and 1.5 %. From the 199th to the 201st harmonic, it is equal to 4.21 % and 4.23 % respectively and from the 205th to the 229th harmonic, it is between 1.5 % and 1 %.

Alternative phase disposition opposition (APOD): from the 171st to the 181st harmonic, the harmonic amplitude related to the fundamental is less than 1 %. From the 183rd to the 217th harmonic, it varies between 1.24 % and 2.2 % and from the 219th to the 229th harmonic, it is less than 1 %.

Alternative phase disposition (APD):from the 171st to the 181st harmonic, the harmonic amplitude related to the fundamental is less than 1 %. From the 183rd to the 217th harmonic, it varies between 1.16 % and 1.91 % and from the 219th to the 229th harmonic, it is less than 1 %.

4. Conclusion.

In this paper, two SPWM control strategies of H bridge fifteen level inverter are presented. The triangular multicarrier SPWM and the saw tooth multicarrier SPWM. In addition of SPWM techniques, different modulation strategies as phase disposition (PD) , phase opposition disposition (POD), alternative phase opposition disposition (APOD) and shifted phase (APD) are implemented in PSIM environment for a switch frequency of 10 kHz, for modulation indexes of 0.8, 0.9 and 1.

Total harmonic distortion were measured, grouped and analysed.

It is found that The phase disposition (PD) has the best total harmonic distortion THD and the phase opposition disposition (POD) has the worst THD for both the SPWM control techniques.

Despite the fact that the difference of THD between triangular multicarrier SPWM and saw tooth multicarrier SPWM is less than 1 % (0.02 % to 0.93 %), there is no denying the superiority of the saw tooth multicarrier SPWM compared to the triangular multicarrier SPWM.

References:

1. **Y. Sahali et M. K. Fellah**: *Principe de la compensation Harmonique des Ondes Multiniveaux.* **In:Conférence on Electrical Engineering, 10-11 December 2002, Batna-ALGERIA.**
2. **F. Wang**: *Sine-Triangle vs. Space Vector Modulation for Three-Level PWM Voltage Source Inverters.* **In: Conf. Rec. IEEE IAS , Annual Meeting 2000, pp.2482-2488.**
3. **G Durga Prasad, Dr. V Jegathesan , Dr. P V V Rama Rao**: *Total Harmonic Distortion, Distortion Factor & Crest Factor in Sven Level Cascaded H-Bridge Inverter for Different PWM Control Strategies: A Comparative Study .* **In:International Journal of Electrical Engineering, Number 3 (2014), Volume 7, pp. 377-389 .**
4. **Sagar U. Shinde, Mithun Aush, Dr. K. Vadirajacharya**: *Performance Analysis of VLSI Based Multilevel Inverter.* **In:International Conference on Innovations in EngineeringandTechnology(ICIET'14),   March 21-22, 2014, College of Engineering, Madurai, Tamil Nadu, India.**
5. **D.Mohan and Sreejith B.Kurub**: *A Comparative Analysis of Multi Carrier SPWM Control Strategies using Fifteen Level Cascaded H – bridge Multilevel Inverter.* **In:International Journal of Computer Applications, March 2012, Volume 41– No.21.**
6. **Anupama Gupta1, Shimi S.L**: *Comparative Analysis of Cascaded H- Bridge Inverter and RV Inverter Topology.* **In:International Journal of Science and Research (IJSR).**
7. **Shivpal R Verma, Prof. Preeti V Kapoor:** *Analysis of Three and Five Level Half-Bridge Modular Multilevel Inverter.* **In:International Conference on Industrial Automation and Computing (ICIAC), April 12-13, 2014.**
8. **Joseph Song Manguelle**: *Convertisseurs multiniveaux asymetriques alimentés par transformateurs multi-secondaires basse-fréquence: réactions au reseau d'alimentation.* **Ecole Polytechnique Fédérale de Lausanne. Suisse, thèse No3033, 2004.**
9. **B.P.McGrath, D.G.Holmes**: *Multicarrier PWM strategies for multilevel inverters.* **In:IEEE transactions on power electronics, Vol.49, No4, pp.858-867, Aug 2002.**
10. **Dr. Hina Chandwani, Himanshu N Chaudhari, Dhaval Patel:** *Analysis and simulation of multilevel inverter sing multi carrier based pwm control technique.* **In:International Journal Of Electrical Engineering & Technology (IJEET) Volume 4, pp. 200-208, May - June 2013.**
11. **T.Sengolrajan,   B.Shanthi,   S.P.Natarajan**: *Evaluation of Various Multicarrier SPWM Strategies For Single Phase Seven Level Cascaded Quasi-Z-Source Inverter.* **In: Journal of Theoretical and Applied Information Technology, Vol. 59 No.3, January 2014.**
12. **T.Sengolrajan,   B.Shanthi,   S.P.Natarajan**: *Comparative Study of Multicarrier PWM Techniques for Seven Level Cascaded Z-Source Inverter.* **In: International Journal of Computer Applications , Volume 65– No.6, March 2013.**
13. **Z. Du, L. M. Tolbert, S. Member, B. Ozpineci, J. N. Chiasson**: *Seven-Level Hybrid Cascaded H-Bridge Multilevel Inverter.* **In:IEEE Transactions On Power Electronics, pp. 25-33, 2009.**
14. **Ms.T.Prathiba, Dr.P.Renuga**: *Multi Carrier PWM Based Multi Level Inverter For High PowerApplications.* **In:Int Journal of Computer Applications, vol.1, n. 9, pp 67-71, 2010.**
15. **A.Mahendran, K.Muthulakshmi, R.Nagarajan:** *Triangular Multicarrier SPWM Technique for Nine Level Cascaded Inverter.* **In:International Journal of Scientific & Engineering Research, Volume 4, Issue 5,May 2013.**

16. **V.Hema maheshwari, G.Soundradevi, B.Karthikeyan,G.Sundari:** *A 11 level cascaded multilevel inverter using hybrid modulation technique*. **In:International Journal of Emerging Trends in Engineering and Development Issue 3, Vol.2, March 2013**.

NOMENCLATURES

N: Level number of the output voltage.
P: Number of stages per phase.
m: Modulation index.
r: Modulation rate.
A_r:Sinusoidal reference amplitude.
A_p:Carrier amplitude.
F_r:Sinusoidal reference frequency.
F_p:Carrier frequency.
V_{ab}:Phase voltage waveform.
THD:Total harmonic distortion.