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# SPWM Techniques for Fifteen Level Flying Capacitor Inverter

Farouk Hadjbenali[a], Fouad Azzouz[b]

Department of Electrical Engineering, University of Sciences and Technology of Oran Mohamed Boudiaf, Oran, Algeria
[a]e-mail: farouk.hadjbenali@univ-usto.dz, farouk0409@hotmail.com
[b]e-mail: azzouz.fouad@gmail.com

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***Abstract***— In this paper, different sinusoidal pulse width modulation (SPWM) control strategies of multilevel flying capacitor inverter are presented. Three control strategies are studied; the triangular multicarrier SPWM, the saw tooth multicarrier SPWM and the sinusoidal multicarrier SPWM. This work begins with a presentation of the flying capacitor inverter. Then a paragraph that gives a brief review of the triangular multicarrier SPWM, the saw tooth multicarrier SPWM and the sinusoidal multicarrier SPWM. A comparison between the three SPWM control strategies is established based on the simulation results. The comparison objects are the root mean square rms of the output voltage and the total harmonic distortion (THD). The results obtained demonstrate that the sinusoidal multicarrier SPWM is better than the saw tooth multicarrier SPWM and the triangular multicarrier SPWM. Simulations are carried out by PSIM program.

***Keywords***— Flying capacitor multilevel inverter, Saw tooth multicarrier SPWM, Sine multicarrier SPWM, SPWM, Triangular multicarrier SPWM.

## I. INTRODUCTION

In recent years, there has been a renewed interest in the study of multi-level inverter techniques [1]. Over the last two decades, many PWM control strategies of multilevel inverters have been studied in order to improve the output signals of these inverters [2]. Among the control strategies, we distinguish three PWM strategies: the SPWM, the SVPWM [3] and the selective harmonic elimination PWM [4].
Amongst the PWM control strategies, the SPWM is the most used to multilevel inverters because of its simplicity and ease of implementation [2]. The paper begins with a presentation of the flying capacitor multilevel inverter followed by a recall of the sinusoidal pulse width modulation SPWM. The triangular multicarrier SPWM, the sinusoidal multicarrier SPWM and the saw tooth multicarrier SPWM control strategies are defined in the following section. Finally, a discussion of the simulated results is presented.

## II. FLYING CAPACITOR MULTILEVEL INVERTER

The flying capacitor multilevel inverter or the multicellular converter is an energy conversion topology based on the series connection of the controlled switches. It appeared in the early 1990s with a patent deposited by Meynard and Foch [5].
This inverter is obtained by the connection of clamped capacitor cells [6]. The first benefit of this topology is the absence of clamping diodes inherent to NPC inverter topology. Moreover, the voltage stress imposed to power components is naturally limited; there is a small value of *dv/dt* across the components [7]-[8]. Switching redundancies in operation sequences introduce states that can be used to keep the capacitor charge balance. Thus, a single dc supply is necessary by phase.
In usual working patterns, voltages across capacitors are balanced. The voltage across the capacitors is equal to:

Corresponding author's e-mail: farouk0409@hotmail.com

$$U_{ck}=1-(k/(N-1)) \quad (1)$$

$$k= 1, 2, 3,\ldots(N\text{-}2) \quad (2)$$

where $U_{ck}$ is the voltage across the capacitors; $k$ is the rank of capacitor; and $N$ is the number of levels of the output voltage.
Fig. 1 shows a one-leg flying capacitor fifteen level inverter.

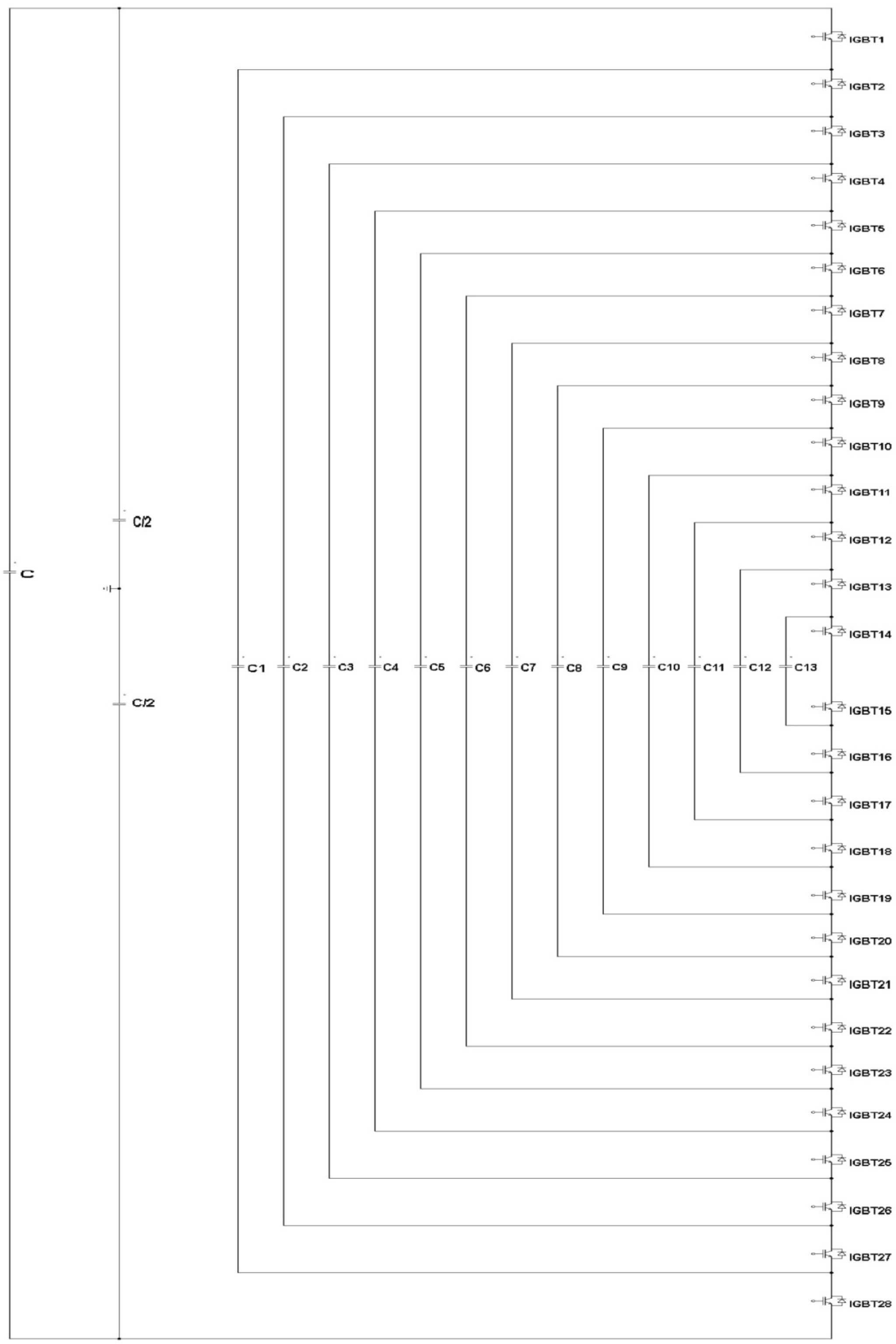

Fig. 1. Power circuit of a one-leg flying capacitor fifteen level inverter

## III. 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 $A_p$ [9]. 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 decoded, and gives the corresponding value to each voltage level [10].

In this paper, three carrier based SPWM techniques are developed as follows [11]:

- Triangular multicarrier SPWM
- Saw tooth multicarrier SPWM
- Sine multicarrier SPWM

### *A. Triangular Multicarrier SPWM (TM SPWM)*

This strategy is based on the comparison of a sine wave reference voltage $U_r$ called a modulating signal with an amplitude $A_r$ and a frequency $F_r$ to one or more triangle carriers $U_p$ that have the same amplitude:

$$A_p=2/(N-1) \tag{3}$$

and the same frequency $F_p$.

For $N$ level inverter, ($N$-1) level carriers [12] with the same frequency $F_p$ and the same peak amplitude $A_p$ are disposed to make the bands they occupy contiguous [13].

The modulation index is:

$$m=A_r/((N-1)\,A_p) \tag{4}$$

and the modulation rate is:

$$R=F_p/F_r \tag{5}$$

The SPWM control strategies are implemented using triangular multicarrier signals for a fifteen level flying capacitor as shown in Fig. 2.

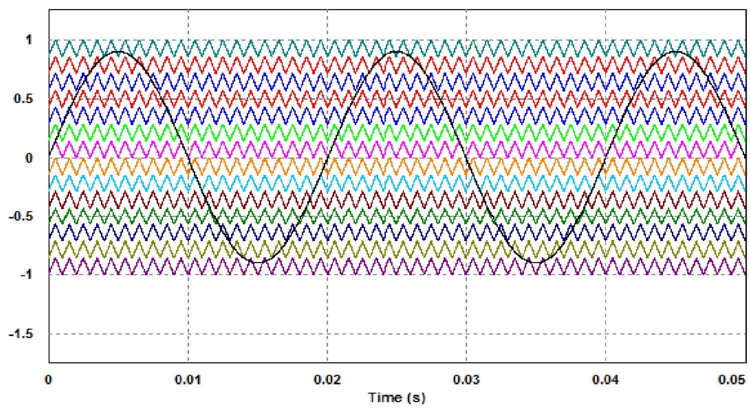


Fig. 2. Reference voltage and triangle multicarrier for a fifteen multilevel inverter ($r$=20, $m$=0.9)

### *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 [2].

The modulation index is:

$$m=A_r/((N–1)\ A_p) \tag{6}$$

and the modulation rate is:

$$R=F_p/F_r \tag{7}$$

The SPWM control strategies are implemented using saw tooth multicarrier signals for a fifteen level flying capacitor as shown in Fig. 3.

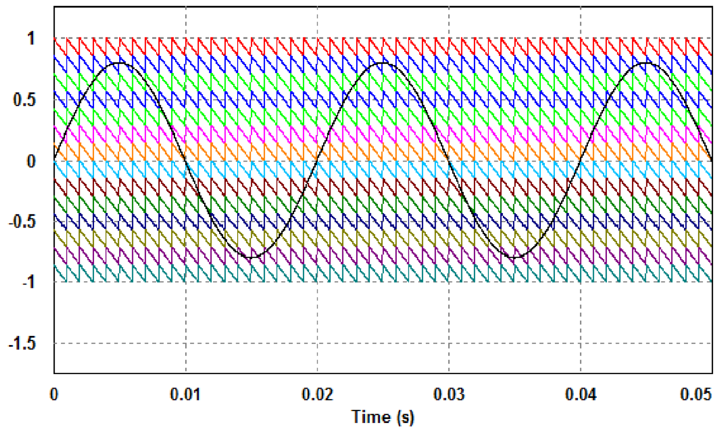


Fig. 3. Reference voltage and saw tooth multicarrier for a fifteen multilevel inverter ($r$=20, $m$=0.8)

### *C. Sine Multicarrier SPWM (SM SPWM)*

In this SPWM technique, a triangular multicarrier is replaced by sinusoidal multicarrier. The representative curve $y=\sin(x)$ accepts the origin as symmetry center, the same goes for all the points, where the curve crosses the x axis .The surfaces of a positive half cycle and a negative half cycle are equal. The function average taken over a period is thus neutral. So, the sine function is an alternate function.

For $N$ level inverter, ($N$-1) level carriers have the same frequency $F_p$ and the same peak amplitude $A_p$.

The modulation index is:

$$m=A_r/(2(N–1)\ A_p) \tag{9}$$

and the modulation rate is:

$$R=F_p/F_r \tag{10}$$

The SPWM control strategies are implemented using sinusoidal multicarrier signals for a fifteen level flying capacitor as shown in Fig. 4.

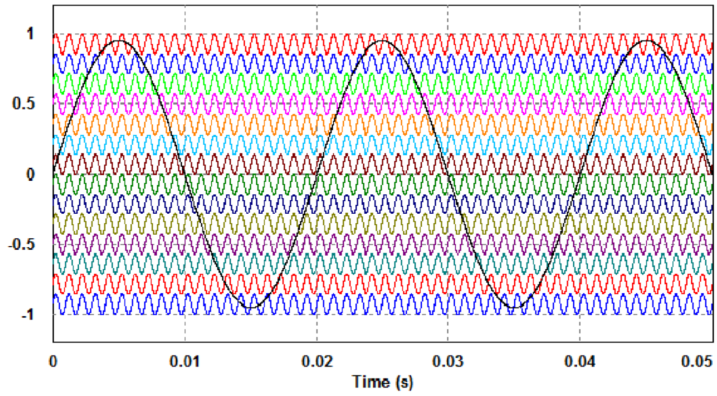


Fig. 4. Reference voltage and sine multicarrier for a fifteen multilevel inverter ($r$=20, $m$=0.95)

## IV. Simulation Results

In order to know which of the triangle multicarrier, saw tooth multicarrier or sine multicarrier has the highest performances, a comparative study based on the total harmonic distortion (THD) and root mean square (RMS) value of the output voltage $V_{ab}$ for the three types of carriers is made.

Fifteen level flying capacitor inverter simulations are carried out by PSIM program. In order to get the THD of the output waveform, a Fast Fourier Transform (FFT) of PSIM program is applied to obtain the spectrum of the output voltage $V_{ab}$.

We have chosen the interval 0.8 to 0.95 of the modulation index since it is the best interval at the SPWM operating level (the number of intersection points between the modulating signal and carriers is much greater than the other modulation index values).

If the modulation index is less than 0.8, the SPWM is undersized. On the other hand, if the modulation index is greater than 0.95, the SPWM is oversized.

### *A. Triangular Multicarrier SPWM (TM SPWM)*

Fig. 5 and Fig. 6 show the voltage waveform $V_{ab}$ and harmonic spectra for the triangular multicarrier with $m$=0.8 and a switching frequency of 10kHz, respectively.

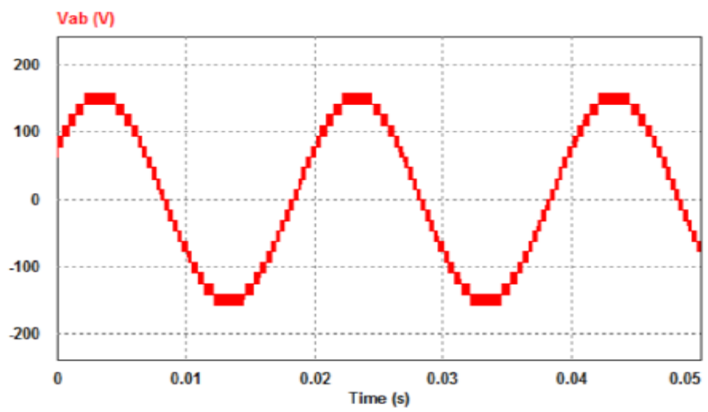


Fig. 5. Output voltage $V_{ab}$ of triangular multicarrier SPWM

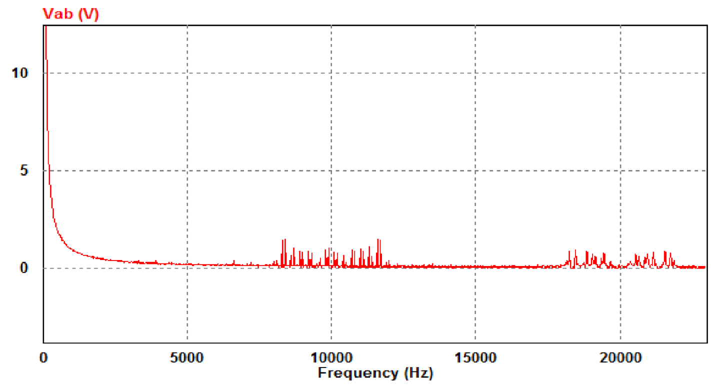


Fig .6. FFT analysis of triangular multicarrier SPWM

Fig. 7 and Fig. 8 show the voltage waveform $V_{ab}$ and harmonic spectra for the triangular multicarrier with $m$=0.9 and a switching frequency of 10kHz, respectively.

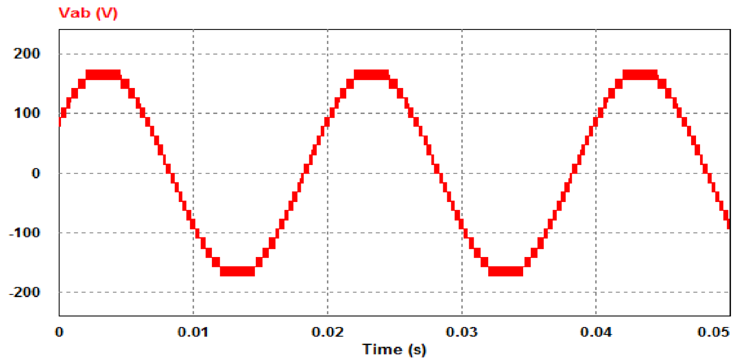


Fig. 7.Output voltage $V_{ab}$ of triangular multicarrier SPWM

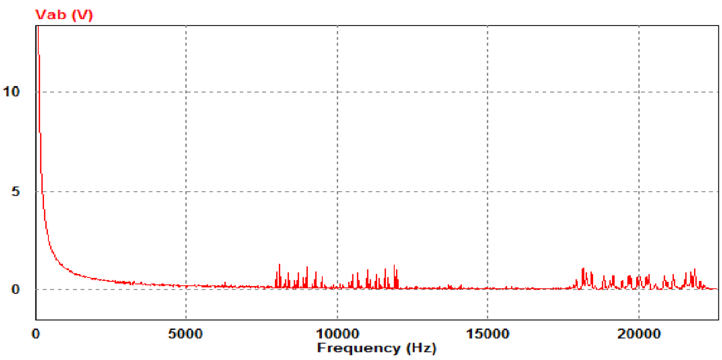


Fig. 8. FFT analysis of triangular multicarrier SPWM

Fig. 9 and Fig. 10 show the voltage waveform $V_{ab}$ and harmonic spectra for the triangular multicarrier with $m$=0.95 and a switching frequency of 10kHz, respectively.

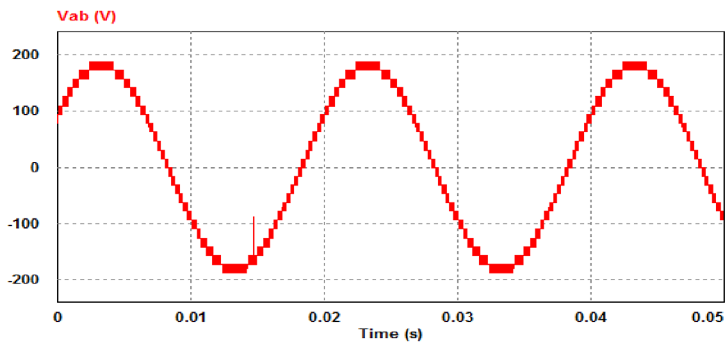


Fig. 9. Output voltage $V_{ab}$ of triangular multicarrier SPWM

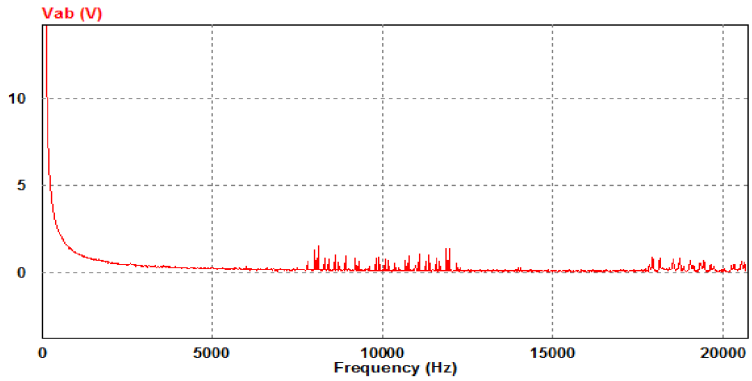


Fig. 10. FFT analysis of triangular multicarrier SPWM

Table 1 shows THD and RMS value of the output voltage $V_{ab}$ for a fifteen level flying capacitor inverter with triangular multicarrier signals for the SPWM control strategy and a switching frequency of 10kHz for the modulation index of 0.8, 0.9 and 0.95.

TABLE 1
THD (%) AND RMS (V) OF THE OUTPUT VOLTAGE

| *m* | THD, % | RMS, V |
|---|---|---|
| 0.8 | 6.14 | 108.02 |
| 0.9 | 5.28 | 121.41 |
| 0.95 | 5.13 | 128.22 |

### *B. Saw Tooth Multicarrier SPWM (STM SPWM)*

Fig. 11 and Fig. 12 show the voltage waveform $V_{ab}$ and harmonic spectra for the saw tooth multicarrier with $m$=0.8 and a switching frequency of 10kHz, respectively.

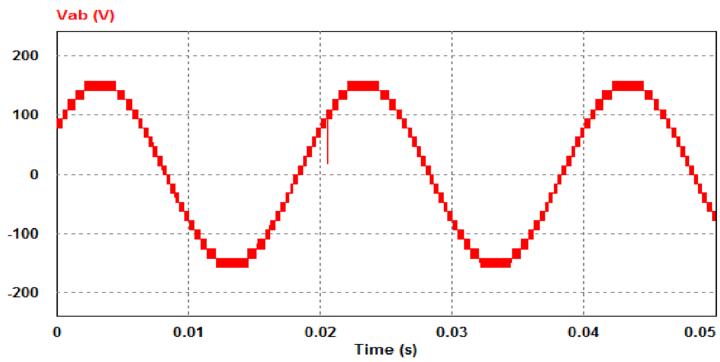


Fig. 11. Output voltage $V_{ab}$ of saw tooth multicarrier SPWM

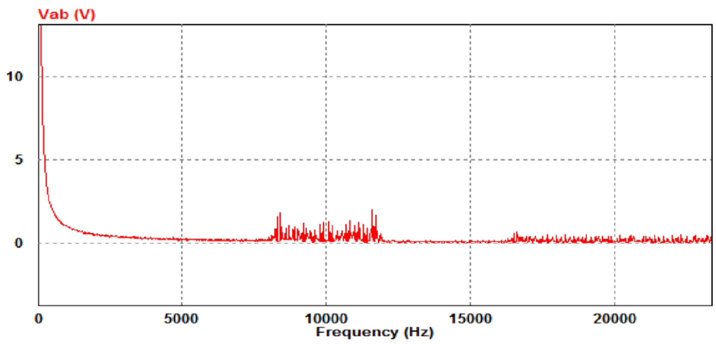


Fig. 12. FFT analysis of saw tooth multicarrier SPWM

Fig. 13 and Fig. 14 show the voltage waveform $V_{ab}$ and harmonic spectra for the saw tooth multicarrier with $m$=0.9 and a switching frequency of 10kHz, respectively.

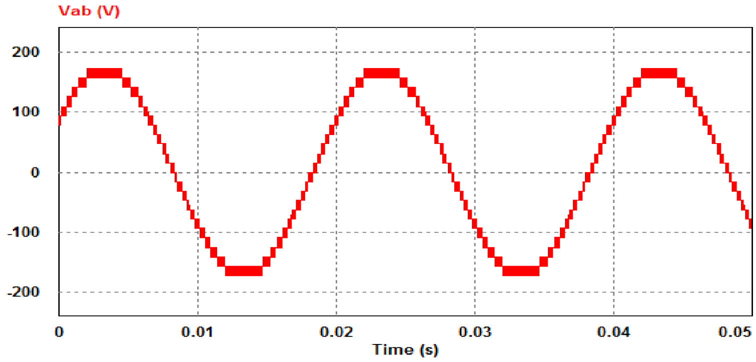


Fig. 13.Output voltage $V_{ab}$ of Saw tooth multicarrier SPWM

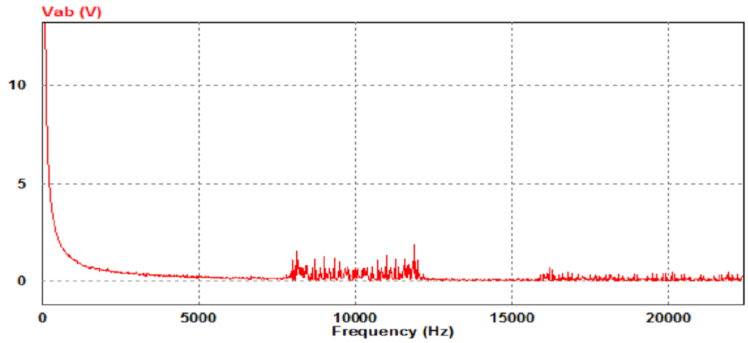


Fig. 14. FFT analysis of saw tooth multicarrier SPWM

Fig. 15 and Fig. 16 show the voltage waveform $V_{ab}$ and harmonic spectra for the saw tooth multicarrier with $m$=0.95 and a switching frequency of 10kHz, respectively.

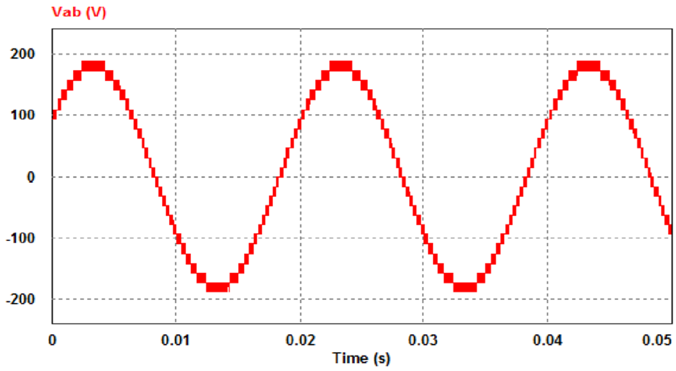


Fig. 15.Output voltage $V_{ab}$ of saw tooth multicarrier SPWM

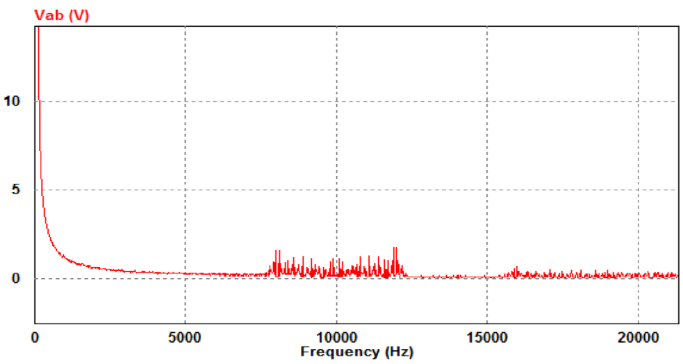


Fig. 16. FFT analysis of saw tooth multicarrier SPWM

Table 2 shows THD and RMS value of the output voltage $V_{ab}$ for a fifteen level flying capacitor inverter with the saw tooth multicarrier signals for the SPWM control strategy and a switching frequency of 10kHz for the modulation index of 0.8, 0.9 and 0.95.

TABLE 2
THD (%) AND RMS (V) OF THE OUTPUT VOLTAGE

| *m* | THD, % | RMS, V |
|---|---|---|
| 0.8 | 6.12 | 108.07 |
| 0.9 | 5.23 | 121.34 |
| 0.95 | 5.11 | 128.16 |

### *C. Sine Multicarrier SPWM (SM SPWM)*

Fig. 17 and Fig. 18 show the voltage waveform $V_{ab}$ and harmonic spectra for the sine multicarrier with *m*=0.8 and a switching frequency of 10kHz, respectively.

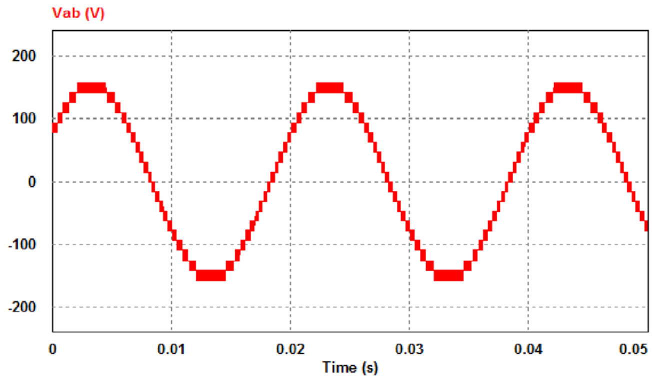


Fig. 17. Output voltage $V_{ab}$ of sine Multicarrier SPWM

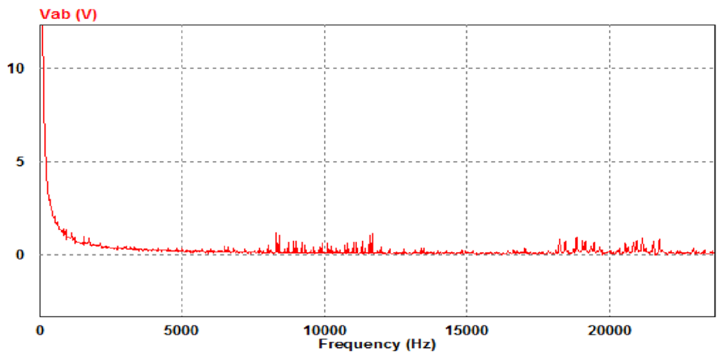


Fig. 18. FFT analysis of sine multicarrier SPWM

Fig. 19 and Fig. 20 show the voltage waveform $V_{ab}$ and harmonic spectra for the sine multicarrier with *m*=0.9 and a switching frequency of 10kHz, respectively.

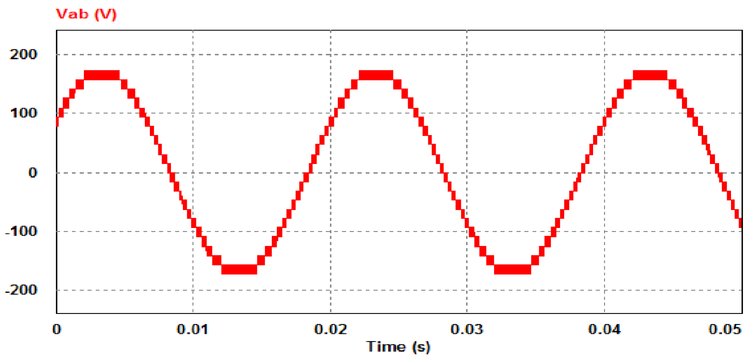


Fig. 19. Output voltage $V_{ab}$ of sine multicarrier SPWM

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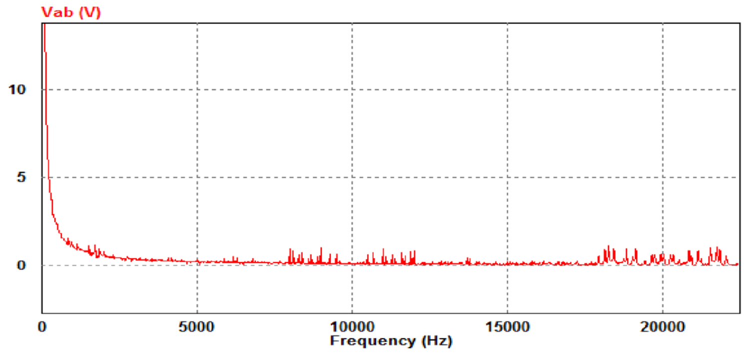


Fig. 20. FFT analysis of sine multicarrier SPWM

Fig. 21 and Fig. 22 show the voltage waveform $V_{ab}$ and harmonic spectra for the sine multicarrier with $m$=0.95 and a switching frequency of 10kHz, respectively.

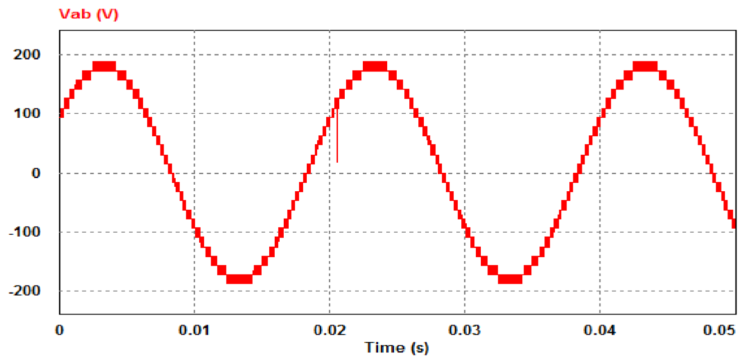


Fig. 21. Output voltage $V_{ab}$ of sine multicarrier SPWM

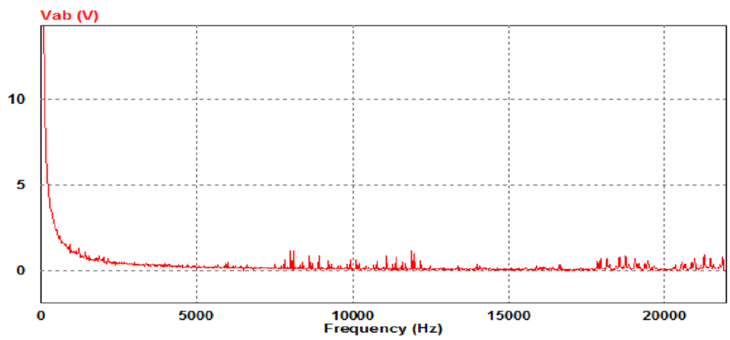


Fig. 22. FFT analysis of sine multicarrier SPWM

Table 3 shows THD and RMS value of output voltage $V_{ab}$ for a fifteen level flying capacitor inverter with the sine multicarrier signals for the SPWM control strategy and a switching frequency of 10kHz for the modulation index of 0.8, 0.9 and 0.95.

TABLE 3
THD (%) AND RMS (V) OF THE OUTPUT VOLTAGE

| ***m*** | **THD, %** | **RMS, V** |
|---|---|---|
| 0.8 | 5.93 | 108.12 |
| 0.9 | 5.39 | 121.8 |
| 0.95 | 4.99 | 128.03 |

## V. Analysis of Results

According to the tables above, we find that the increase in modulation index leads to the increase of the RMS value and the decrease of THD for the three multicarrier signals of the SPWM control strategy. Except for the THD, the decrease is relative for each multicarrier signal of the SPWM control strategy.
For a modulation index of 0.8, THD value is equal to 6.14% in the triangular multicarrier, 6.12% in the saw tooth multicarrier and 5.93% in the sine multicarrier. It can be seen that for $m$= 0.8, the sine multicarrier has the least THD.
For a modulation index of 0.9, THD value is equal to 5.28% in the triangular multicarrier, 5.23% in the saw tooth multicarrier and 5.39% in the sine multicarrier. It can be seen that for $m$= 0.9, the saw tooth multicarrier has the least THD.
For a modulation index of 0.95, THD value is equal to 5.13% in the triangular multicarrier, 5.11% in the saw tooth multicarrier and 4.99% in the sine multicarrier. It can be seen that for $m$= 0.95, the sine multicarrier has the least THD.

## VI. Conclusion

In this paper, three SPWM control strategies of a flying capacitor fifteen level inverter are presented: the triangular multicarrier SPWM, the saw tooth multicarrier SPWM and the sine multicarrier SPWM. The three SPWM control strategies are implemented in PSIM environment for a switch frequency of 10kHz and modulation indices of 0.8, 0.9 and 0.95. THD and RMS values were measured, grouped and analyzed. Despite the fact that the THD difference between triangular multicarrier SPWM, saw tooth multicarrier SPWM and sine multicarrier SPWM is less than 1%, the sine multicarrier SPWM is superior to the triangular multicarrier SPWM and saw tooth multicarrier SPWM.

## References


[1] Y. Sahali, M. Fellah, "Principe de la compensation harmonique des ondes multiniveaux," *Proceedings of IEEE Conférence on Electrical Engineering,* 2002.

[2] F. Hadjbenali and F. Azzouz, "Comparison of cascaded fifteen level inverter multicarrier SPWM strategies," *Journal of Electrical Engineering*, vol. 15, no. 3, pp. 170-179, 2015.

[3] F. Wang, "Sine-triangle vs. space vector modulation for three-level PWM voltage source inverters," *IEEE Transactions on Industry Applications*, vol. 38, no. 2, pp. 500-506, 2002.

[4] G. Prasad, V. Jegathesan and P. Rao, "Total harmonic distortion, distortion factor and crest factor in seven level cascaded h-bridge inverter for different PWM control strategies: a comparative study," *International Journal of Electrical Engineering*, vol. 7, no. 3, pp. 377-389, 2014.

[5] T. Meynard and H. Foch, "Multi-level choppers for high voltage applications," *European Power Electronics and Drives*, vol. 2, no. 1, pp. 45-50, 1992.

[6] F. Hadjbenali and F. Azzouz, "Comparison of flying capacitor fifteen level inverter and thirty three level inverter PWM control strategies," *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 6, no. 2, pp. 368-378, 2017.

[7] F. Ueda, M. Asao and K. Tsuboi, "Parallel-connections of pulse width modulated inverters using current sharing reactors," *IEEE Transactions on Power Electronics*, vol. 10, no. 6, pp. 673-679, 1995.

[8] K. Corzine, M. Wielebski, F. Peng and J. Wang, "Control of cascaded multi-level inverters," *IEEE Transactions on Power Electronics*, vol. 19, no. 3, pp. 732-738, 2004.

[9] S. Verma and P. Kapoor, "Analysis of three and five level half-bridge modular multilevel inverter," *Proceedings of International Conference on Industrial Automation and Computing*, pp. 59-62, 2014.

[10] J. Manguelle, *Convertisseurs Multiniveaux Asymétriques Alimentés Par Transformateurs Multi-Secondaires Basse-Fréquence,* Doctorate Thesis, Ecole Polytechnique Fédérale de Lausanne (Suisse), 2004.

[11] B. McGrath, D. Holmes, "PWM strategies for multilevel inverters," *IEEE Transactions on Power Electronics*, vol. 49, no. 4, pp.858-867, 2002.

[12] T. Prathiba and P. Renuga, "Multi carrier PWM based multi level inverter for high power applications," *International Journal of Computer Applications*, vol. 1, no. 9, pp. 67-71, 2010.

[13] A. Mahendran, K. Muthulakshmi and R. Nagarajan, "Triangular multicarrier SPWM technique for nine level cascaded inverter," *International Journal of Scientific & Engineering Research*, vol. 4, no. 5, pp. 269-275, 2013.