

Comparison of Flying Capacitor Fifteen Level Inverter and Thirty Three Level Inverter PWM Control Strategies

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Abstract

In the paper two PWM control strategies of multilevel flying capacitor inverter is proposed. The study starts with a presentation of the Flying capacitor inverter and the two PWM control strategies (SPWM and Suboptimal PWM). Then a section which presents a brief recall of the triangular multicarrier PWM and the sinusoidal multicarrier PWM. A comparison between the two PWM control strategies based on the simulation results is made. The subjects of comparison are the root mean square rms of the output voltage and the total harmonic distortion THD. The obtained results have proved that the Suboptimal PWM is better than the SPWM. Simulations are carried out by PSIM program.

Keywords: Flying capacitor multilevel inverter, SPWM, suboptimal PWM, triangular multicarrier, sinusoidal multicarrier

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1. Introduction

The concept of multilevel converters has been introduced since 1975 [1-2]. The term multilevel began with the three-level converter [3]. Subsequently, several multilevel converter topologies have been developed [4]. The main motivations behind multilevel inverters are on one hand the increase of power through the voltage generation of higher voltage beyond those compatible with cut off voltages of power semiconductor devices; on the other hand we seek to obtain output quantities that present a reduced harmonic content [5]. The benefit of multilevel inverter use lies in their ability to generate waveforms of good quality, a decrease commutation frequency, a reduction of power losses, and a lessening of static component strain. The multilevel inverters still require many improvements and optimization in the control area. Among these control strategies, we distinguish three PWM structures; the SPWM, the SVPWM [6], and the SHEWPM [7]. Optimized harmonic-stepped waveform (OHSW) and optimal minimization of THD (OMTHD) are used for harmonic optimization [8].

This study is dedicated to the improvement of the rms and the total harmonic distortion of the output voltage by the level increase of flying capacitor multilevel inverter until 33 levels along with the optimization of SPWM control strategies.

2. Flying Capacitor Multilevel Inverter

Meynard and Foch introduced a flying-capacitor-based inverter in 1992 [9]. This structure is based on connecting in series commutation cells between which is inserted a floating voltage source. These floating voltage sources are carried out by condensers. The structure of such inverter is similar to that of the NPC inverter except that instead of clamp diodes, the flying capacitor inverter uses capacitors. The main advantages of multilevel flying capacitor converters are as follows [10-11];

1. Phase redundancies are available for balancing the voltage levels of the capacitors [10-11].
2. Real and reactive power flow can be controlled [10-11].
3. The large number of capacitors enables the inverter to ride through short duration outages and deep voltage sags [10-11].

The number of levels is computed by the following formula [12]:

$$N = P + 1$$

N : number of voltage levels.

P : number of complementary switches pairs per phase.

In usual working pattern, voltages across the capacitors are balanced.

The voltage across the capacitors is equal to:

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

$$k = 1, 2, 3, \dots, (N - 2)$$

U_{ck} : voltage across the capacitors

k : rank of capacitor

N : Number of levels of output voltage.

Figure 1 shows a one leg flying capacitor fifteen level inverter.

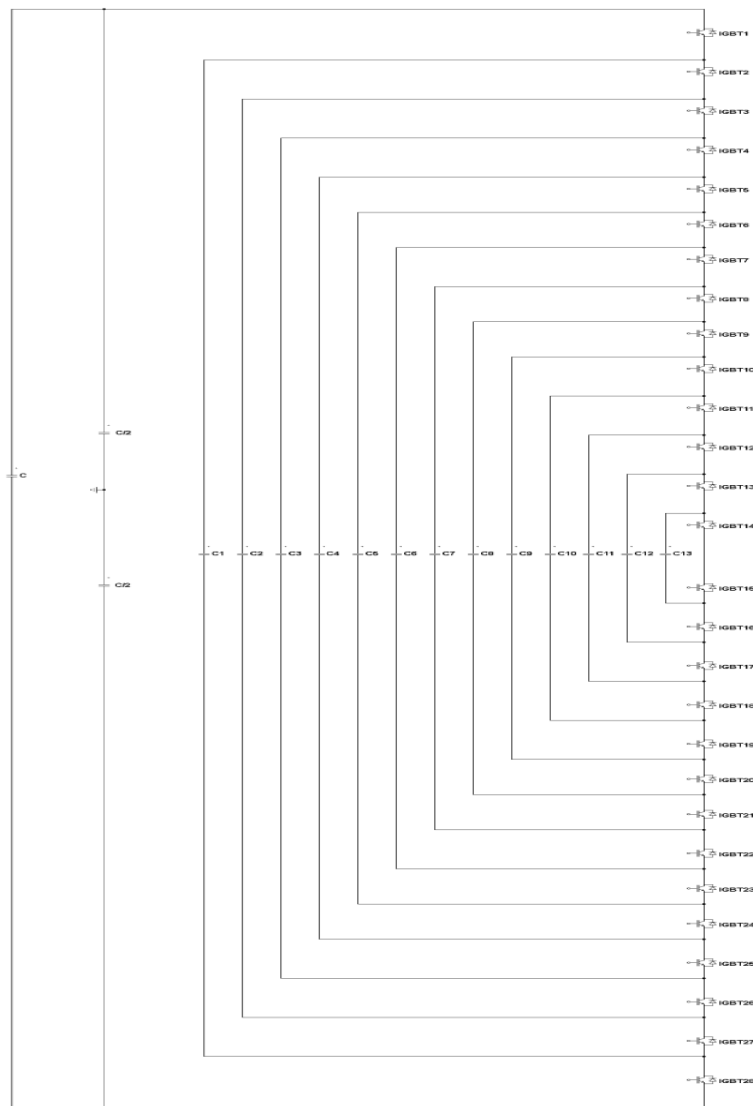


Figure 1. Power circuit of a one leg flying capacitor fifteen level inverter

Figure 2 shows a one leg flying capacitor thirty three level inverter.

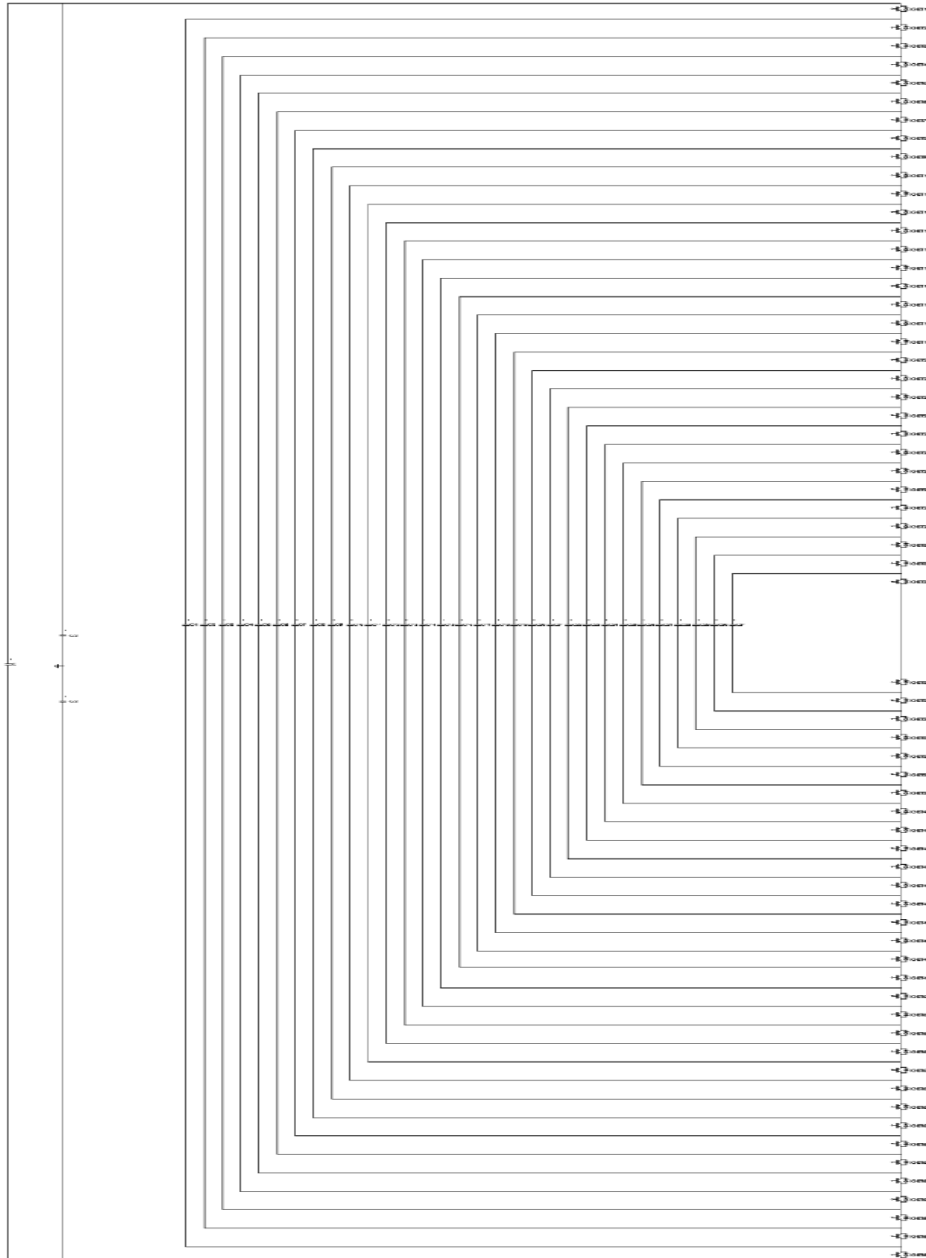


Figure 2. Power circuit of a one leg flying capacitor thirty three level inverter

3. PWM Modulation Strategies

3.1. Sinusoidal Pulse Width Modulation SPWM

Introduced by Schonung in 1964 [13]. In order to generate the output voltage waveform, the sinus wave reference voltage called modulating signal that has an amplitude A_r and a frequency F_r is compared to one or several carriers that have the same amplitude A_p and the same frequency F_p . For a carrier higher or equal to the reference, the comparison gives 1 and 0 if the carrier is below the reference. The number of carriers required to produce N level output is $(N - 1)$.

The *SPWM* is characterized by two parameters:

Modulation index m and Modulation rate r .

In this paper, two carrier based *SPWM* techniques are developed as follows:

1. Triangular Multi carrier *SPWM*.
2. Sinus multi carrier *SPWM*.

3.2. Suboptimal PWM

Optimal *PWM* (or suboptimal) enables to reduce voltage waste by injection of harmonic 3 in the reference (or the modulating) [14], [19]. This control strategy allows us to increase the maximal amplitude of the fundamental of the resulting wave, without that the modulating amplitude does not go beyond $(A_p/2)$ by the injection of harmonic 3 in the modulating signal. This harmonic 3 found in output voltages is eliminated by the three phase system in single voltages and phase to phase voltages [15]. This method is shown by Figure 3.

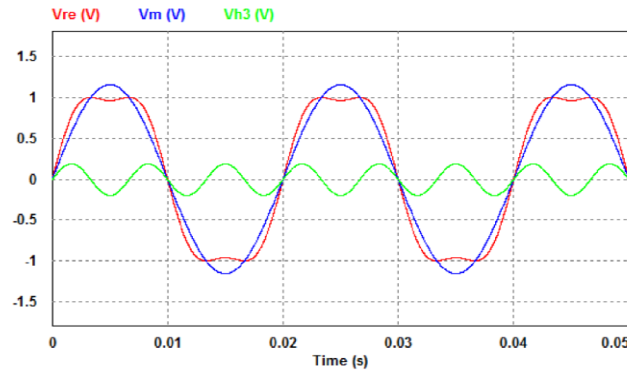


Figure 3. Voltage waveforms: waveform of the resulting voltage V_{re} (red); waveform of the modulating voltage V_m (blue); waveform of the third harmonic voltage V_{h3} (green)

The modulating is expressed as follows:

$$\begin{aligned} V_{re} &= V_m + V_{h3} \\ V_{re} &= A_m \sin(\theta) + A_{h3} \sin(3\theta) \\ A_{h3} &= A_m / 6 \end{aligned}$$

V_{re} : resulting voltage waveform

A_m : modulating amplitude

A_{h3} : harmonic order 3 amplitude

In this paper, two carriers based Suboptimal *PWM* techniques are developed as follows:

1. Triangular Multi carrier Suboptimal *PWM*
2. Sinus multi carrier Suboptimal *PWM*

In our study we use the *SPWM* and the Suboptimal *PWM* control strategies for two kinds of carriers, the triangular multicarrier wave and the sinusoidal multicarrier wave. The output voltage waveform is shown through simulations using *PSIM* for a fifteen and thirty three level flying capacitor inverter.

3.3. Triangular Multicarrier PWM

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

For N level inverter, $(N-1)$ level carriers [16] with the same frequency F_p and the same peak amplitude A_p are disposed such as the bands they occupy are contiguous. They are defined as [17]:

$$\begin{aligned} C_i &= A_p ((-1)^{f(i)} y_p(\omega_c, \varphi) + t - (N/2)) \\ i &= 1, \dots, (N-1) \end{aligned}$$

Where y_p is a normalized symmetrical triangular carrier defined as,

$$y_p = (-1)^{\lfloor \alpha \rfloor} ((\alpha \bmod 2) - 1) + 1/2$$

$$\alpha = (w_c t + \phi) / \pi = 2\pi F_p$$

ϕ represents the phase angle of y_p .

y_p is a periodic function with the period [18]:

$$T_p = 2\pi / w_p$$

Modulation index:

$$m = A_r / ((N-1)A_p)$$

Modulation rate:

$$r = F_p / F_r$$

The *SPWM* and Suboptimal *PWM* control strategies are implemented using triangular multicarrier signals for a 7 level Flying Capacitor. They are shown in Figure 4.

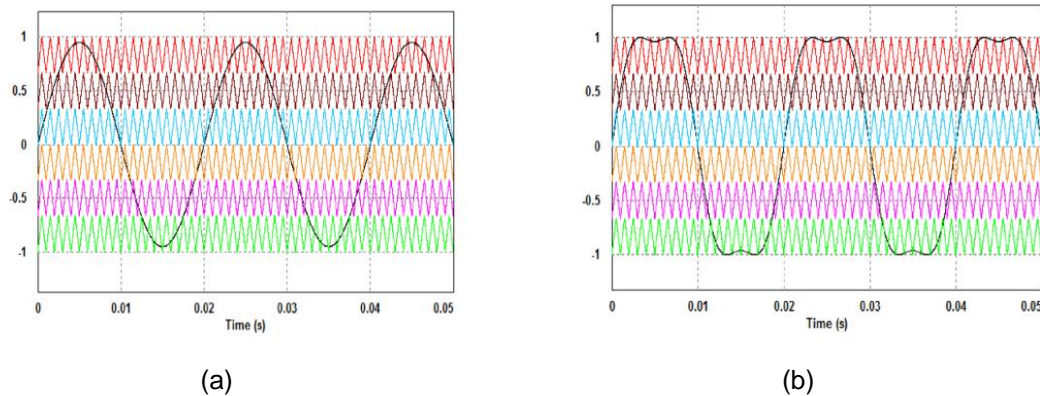


Figure 4. (a) Triangular multicarrier *SPWM*, (b) Triangular multicarrier Suboptimal *PWM*

3.4. Sine Multicarrier PWM

In this *SPWM* technique, triangular multicarriers are replaced by sinusoidal multicarriers. The representative curve of sine wave is $y = \sin(x)$ accepts the origin as symmetry centre. The same goes for all the points where the curve crosses the x axis. The surfaces of positive half cycle and 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 with the same frequency F_p and the same peak amplitude A_p .

Modulation index:

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

Modulation rate:

$$r = F_p / F_r$$

The *SPWM* and Suboptimal *PWM* control strategies are implemented using sinusoidal multicarrier signals for a 7 level Flying Capacitor. They are shown in Figure 5.

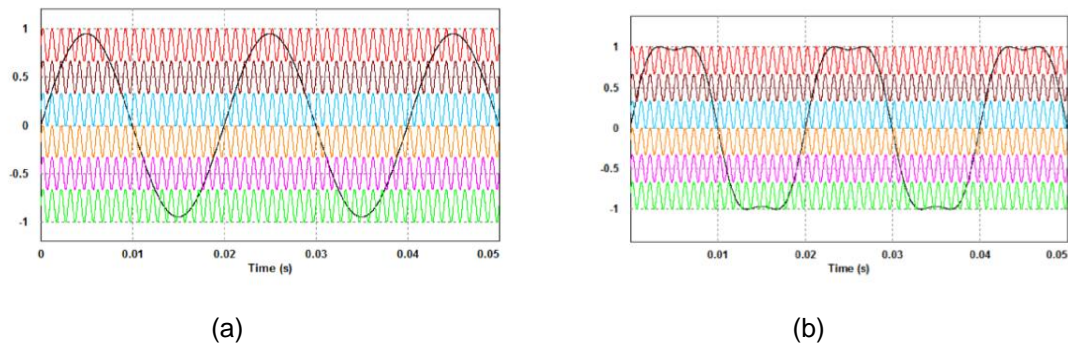


Figure 5. (a) Sinusoidal multicarrier *SPWM*, (b) Sinusoidal multicarrier Suboptimal *PWM*

4. Simulation Results

In order to know which of the two control strategies (*SPWM* and Suboptimal *PWM*) has the highest performances, a comparative study based on the *THD* and the *rms* (*V*) of the output voltage *Vab* (*V*) for the two types of carriers (triangular multicarrier and sinusoidal multicarrier) is done. Fifteen and thirty three 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 phase voltage *Vab* (*V*).

4.1. *SPWM* Control Strategy

Figure 6, Figure 7, Figure 8 and Figure 9 show the phase voltage waveform *Vab* (*V*) and harmonic spectra for the triangular multicarrier with $m=0.95$ and switching frequency of 10 *kHz* for the 15 and 33 level Flying Capacitor inverter respectively.

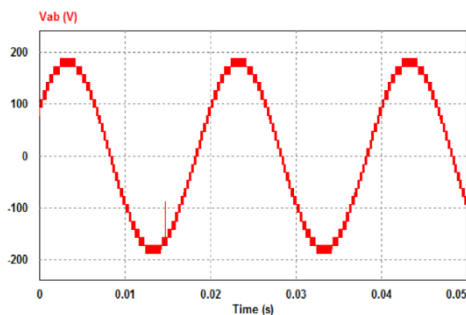


Figure 6. Fifteen level inverter output phase voltage *Vab* (*v*)

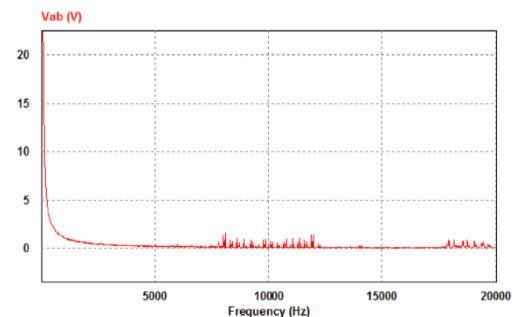


Figure 7. *FFT* analysis of Triangular Multi Carrier *SPWM* for fifteen level inverter

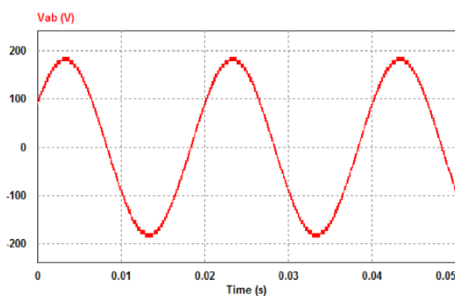


Figure 8. Thirty three level inverter output phase voltage *Vab* (*V*)

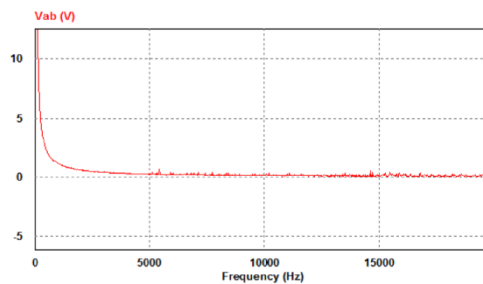


Figure 9. *FFT* analysis of Triangular Multi Carrier *SPWM* for thirty three level inverter

Figure 10, Figure 11, Figure 12 and Figure 13 show the phase voltage waveform $V_{ab}(V)$ and harmonic spectra for the sinusoidal multicarrier with $m=0.95$ and switching frequency of 10 kHz for the fifteen and thirty tree level Flying Capacitor inverter respectively.

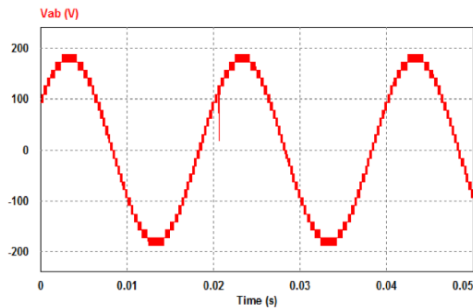


Figure 10. Fifteen level inverter output phase voltage $V_{ab}(V)$

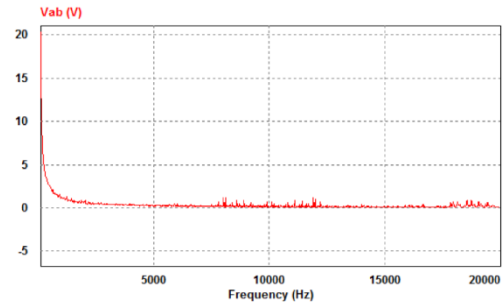


Figure 11. *FFT* analysis of Sinusoidal Multi Carrier *SPWM* for Fifteen level inverter

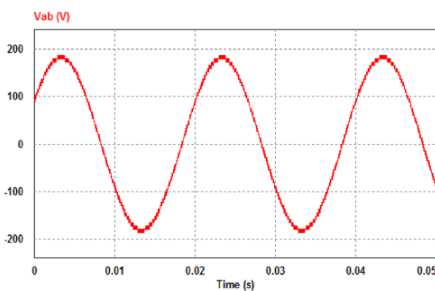


Figure 12. Thirty three level inverter output phase voltage $V_{ab}(V)$

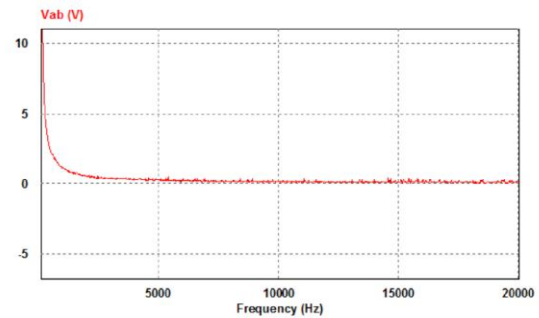


Figure 13. *FFT* analysis of Sinusoidal Multi Carrier *SPWM* for Thirty three level inverter

Table 1 and Table 2 show the total harmonic distortion *THD* and the *rms* (*V*) of output voltage $V_{ab}(V)$ respectively for fifteen and thirty tree level Flying capacitor inverter with the triangular multicarrier and sinusoidal multicarrier signals for the *SPWM* control strategy with a switching frequency of 10 kHz , for modulation index of $m=0.95$.

Table 1. *THD* (%) of output voltage $V_{ab}(V)$

N	Triangle multi carrier	Sinusoidal multi carrier
15	5.13	4.99
33	2.29	2.23

Table 2. The *rms* (*V*) of output voltage $V_{ab}(V)$

N	Triangle multi carrier	Sinusoidal multi carrier
15	128.22	128.03
33	127.96	128.11

According to the tables above, it is observed that when the number of levels of the flying capacitors increases, the total harmonic distortion decreases for the triangular multicarrier and the sinusoidal multicarrier.

From the simulation results, the sinusoidal multicarrier *SPWM* control strategy for the flying capacitor fifteen and thirty three level inverter has the smallest *THD* related to the triangle multicarrier *SPWM* control strategy.

The increase of level number of the flying capacitor inverter has also an influence over the *rms* of output voltage V_{ab} (V). The triangular multicarrier: the *rms* decreases when the level number of flying capacitor increases. The sinusoidal multicarrier: the *rms* increases when the level number of flying capacitor increases.

From the simulation results (Figure 7, Figure 9, Figure 11 and Figure 13):

The fifteen level triangular multicarrier: from the 5th to the 19th harmonic, the harmonic amplitude related to the fundamental is between 4.38% and 1.04%. And from the 20th to the 40th harmonic, the harmonic amplitude related to the fundamental is between 0.98% and 0.58%. And from the 41st to the 400th harmonic, the harmonic amplitude related to the fundamental is less than 0.5%. Except for the 160th, 162nd, 138th and 240th harmonic, the harmonic amplitudes related to the fundamental are 1.07%, 1.29%, 1.12% et 1.09% respectively.

The fifteen level sinusoidal multicarrier: from the 5th to the 19th harmonic, the harmonic amplitude related to the fundamental is between 4.38% and 1.04%. And from the 20th to the 40th harmonic, the harmonic amplitude related to the fundamental is between 0.98% and 0.58%. And from the 41st to the 400th harmonic, the harmonic amplitude related to the fundamental is less than 0.5%. Except for the 160th, 162nd, 138th and 240th harmonic, the harmonic amplitude related to the fundamental are 0.93%, 0.92%, 0.9% et 0.8% respectively.

4.2. Suboptimal PWM Control Strategy

Figure 14, Figure 15, Figure 16 and Figure 17 show the phase voltage waveform V_{ab} (V) and the harmonic spectra for the triangular multicarrier with $A_r=1.155$, $A_h3=0.1925$ and a switching frequency of 10 kHz for the fifteen and thirty three level Flying Capacitor inverter respectively.

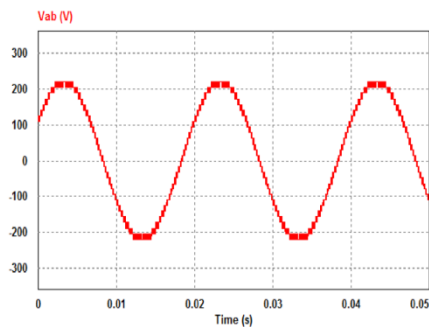


Figure 14. Fifteen level inverter output phase voltage V_{ab} (V)

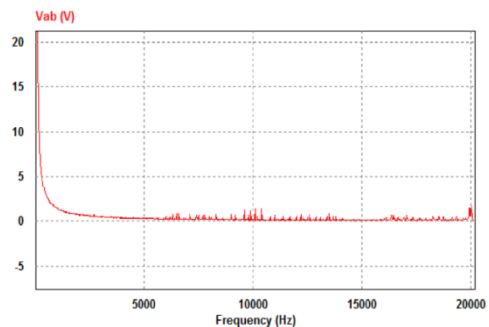


Figure 15. *FFT* analysis of Triangular Multi Carrier Suboptimal *PWM* for fifteen level inverter

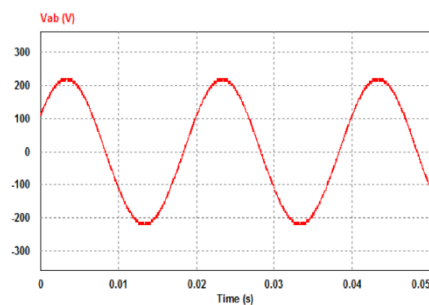


Figure 16. Thirty three level inverter output phase voltage V_{ab} (V)

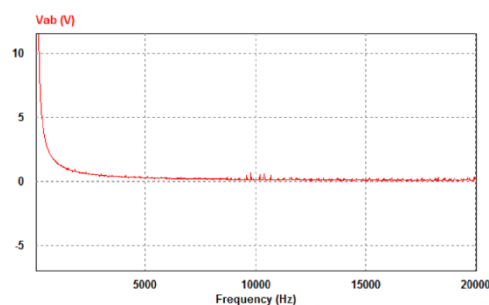


Figure 17. *FFT* analysis of Triangular Multi Carrier Suboptimal *PWM* thirty three level inverter

Figure 18, Figure 19, Figure 20 and Figure 21 show the phase voltage waveform $V_{ab}(V)$ and the harmonic spectra for the sinusoidal multicarrier with $A_r=1.155$, $A_h3=0.1925$ and a switching frequency of 10 kHz for the fifteen and thirty three level Flying Capacitor inverter respectively.

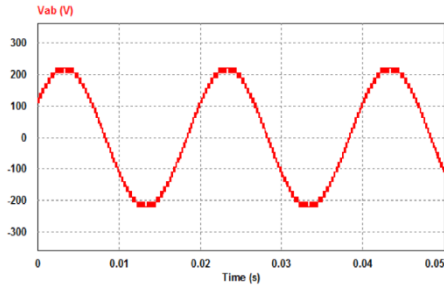


Figure 18. Fifteen level inverter output phase voltage $V_{ab}(V)$

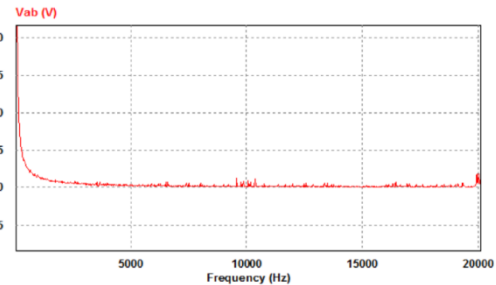


Figure 19. *FFT* analysis of Sinusoidal Multi Carrier Suboptimal *PWM* for fifteen level inverter

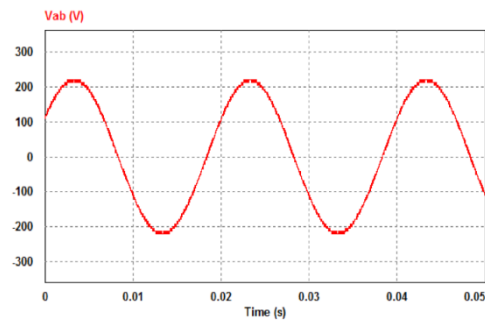


Figure 20. Thirty three level inverter output phase voltage $V_{ab}(V)$

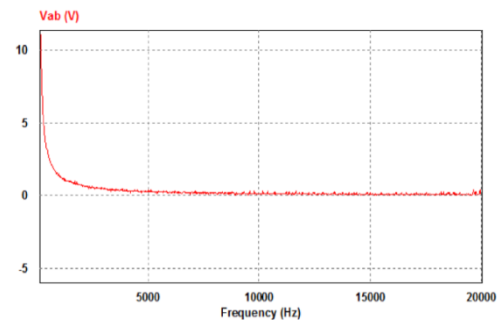


Figure 21. *FFT* analysis of Sinusoidal Multi Carrier Suboptimal *PWM* for thirty three level inverter

Table 3 and Table 4 show the total harmonic distortion *THD* and the *rms* of output voltage $V_{ab}(V)$ respectively for fifteen and thirty tree level Flying capacitor inverter with the triangular multicarrier and sinusoidal multicarrier signals for the Suboptimal *PWM* control strategy with a switching frequency of 10 kHz .

Table 3. *THD* (%) of output voltage $V_{ab}(V)$

N	Triangle multi carrier	Sinusoidal multi carrier
15	4.06	4.23
33	1.79	1.80

Table 4. The *rms* (V) of output voltage $V_{ab}(V)$

N	Triangle multi carrier	Sinusoidal multi carrier
15	155.69	154.41
33	155.60	155.32

According to the tables above, it is observed that when the level number of flying capacitor increases, the total harmonic distortion decreases for the triangular multicarrier and the sinusoidal multicarrier.

From the simulation results, the triangular multicarrier SPWM control strategy for the flying capacitor fifteen level inverter has the smallest THD related to the sinusoidal multicarrier SPWM control strategy.

The increase of level number of flying capacitor has also an influence over the rms value of the output voltage V_{ab} (V). According to the tables 2 and 4, the suboptimal PWM allowed us to deal with the under exploitation flaw of the DC supply E by the SPWM strategy. The rms of applied voltages to the load is increased by adding to the reference sinusoidal the harmonics 3 of the voltage. In our case, the rms voltage is improved up to 70.76 % of E instead of 58.28 % of E in SPWM.

From the simulation results (Figure 15, Figure 17, Figure 19 and Figure 21): The fifteen level triangular multicarrier: from the 5th to the 20th harmonic, the harmonic amplitude related to the fundamental is between 4.38% and 1.01%. And from the 21st to the 39th harmonic, the harmonic amplitude related to the fundamental is between 0.94% and 0.50%. And from the 40th to the 400th harmonic, the harmonic amplitude related to the fundamental is less than 0.5%. Except for the 192nd, 198th, 202nd, 208th and 399th harmonic, the harmonic amplitude related to the fundamental are 0.84%, 0.77%, 0.88%, 0.91% et 1% respectively.

From the simulation results (Figure 7, Figure 9, Figure 11 and Figure 13): The fifteen level sinusoidal multicarrier: from the 5th to the 20th harmonic, the harmonic amplitude related to the fundamental is between 4.37% and 1.01%. And from the 21st to the 40th harmonic, the harmonic amplitude related to the fundamental is between 0.96% and 0.56%. And from the 41st to the 400th harmonic, the harmonic amplitude related to the fundamental is less than 0.5%. Except for the 192nd, 198th, 202nd, 208th and 399th harmonic, the harmonic amplitude related to the fundamental are 0.84%, 0.56%, 0.59%, 0.76% and 1.2% respectively.

5. Conclusion

In this paper SPWM and Suboptimal PWM control strategies of fifteen and thirty three flying capacitor inverter are presented.

The THD and rms are measured, presented and analyzed. It is found that the suboptimal PWM control strategy gives the lowest total harmonic distortion THD and the highest rms of the output voltage for the two types of carriers (triangular multicarrier and sinusoidal multicarrier) compared to the SPWM.

Except that the suboptimal PWM using the triangular multicarrier has the best performance than the suboptimal PWM using the sinusoidal multicarrier for the fifteen and thirty three level flying capacitor inverter.

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