NEW SYMMETRICAL HYBRID MULTILEVEL DC-AC CONVERTERS – THREE-PHASE EXTENSIONS

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Abstract **– This paper presents the analysis and simulation of two new three-phase symmetrical hybrid multilevel inverters. Being these the three-phase extension of the circuits shown in [4]. Also is given its respective commutation pattern with the purpose, to the same that in the single-phase cases, of minimizing the reverse voltage stress that affect the power switches and decreasing the total harmonic distortion (THD) of the load voltage. By this, the circuits are suitable for high power applications. Verifying the theoretical analysis, this made through digital simulations.**

Keywords: **DC-AC Converters, Hybrid Inverters, Symmetrical Multilevel Inverters.**

1. INTRODUCTION

In the recent years specialized literature has shown the emerge of a new family of inverters as one solution, of several, to process of electronic conversion of energy in high voltages, this new generation of inverters is known as voltage source multilevel inverters. Within this classification we can name the Hybrid Multilevel Inverters, focus of the research to be presented.

Reference [1] shows the asymmetrical hybrid multilevel inverter of seven-level voltage. This is based on the binary configuration of the voltage sources, i.e., in load voltage, 2^{N+1}- 1 number of levels can be obtained, being N the total of DC sources in the circuit. The upper full-bridge is composed by switches of great voltage blockade capacity and therefore of low operation frequency (GTO for example), whereas the bottom full-bridge is constituted by switches of high velocity of commutation, but with not much voltage reverse capacity (IGBT for example). Using an appropriate modulation strategy is possible to synthesize waveshapes with seven-level voltage, -3E, -2E, -E, 0, E, 2E and 3E. The modulation strategy includes the hybrid modulation concept, which is based on the unique pulse modulation together with the sinusoidal pulse width modulation (a little complex). Under this modulation strategy, the slow switches are modulated to commutate to the fundamental frequency, the fast switches could be utilized to commutate a higher frequency, and as a result of that providing an improvement in the output waveshape quality. Then, the spectral response of the output voltage would depend on the fast switches, whereas the whole capacity of voltage generation would depend on the slow switches [1].

Although the KVA capacity of the hybrid multilevel inverter devices is the same that in the conventional cascade multilevel inverter, it is possible to obtain a meaningful reduction on the expenses with an appropriate device selection [2].

2. THREE-PHASE SYMMETRICAL HYBRID MULTILEVEL INVERTER, HALF-BRIDGE CONFIGURATION (IH3ϕ-HB -TC)

Reference [4] presents the single phase circuit IH1ϕ-HB-TC, half-bridge configuration, which is shown in figure 1(a). The theoretical output voltage waveform of the circuit is shown in figure 1(b) where it is possible to appreciate this signal has five levels.

If three IH1ϕ-HB-TC are connected, in order that they feed a load in star disposition, then the outcome is a symmetrical three-phase hybrid multilevel inverter (IH3ϕ-HB-TC), as presented in figure 2, where it is observed that the numbers of levels in the load voltage is given by N+1, being N the total of DC sources in the circuit.

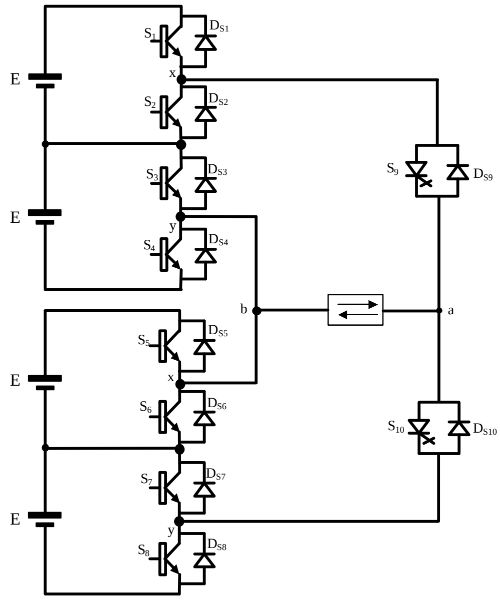
Each one of the modulating signals of the three-phase inverters is out of phase by 120° relative to each other. The common point of the inverters will be named *‘o’*, whereas the common point of the load star connection will be designated *‘n’*. The connection points between each single-phase inverter and the load will be called *‘u’*, *‘v’* and *‘w’*.

2.1. Modulation Strategy

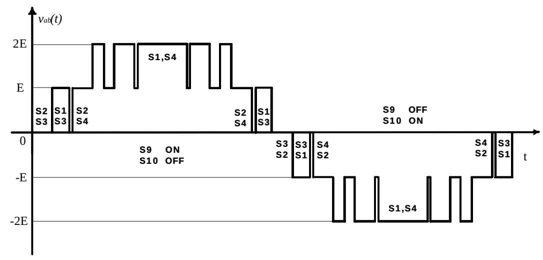
The modulation strategy is the same that was used for the single-phase inverter [4]; with the exception in the modulating signals, as well as the carriers of each single-phase inverter, is horizontally shifted in-phase in 120 degrees to each other. Many different strategies for the multi-level pulse-width modulation (PWM) exist, however we will choice the PWM-strategy which generates the least harmonic content.

Therefore, for each cell the signals are generated through the comparison of a modulating signal V_m with two triangular carrier signals (V_{t1} - V_{t2} for the upper cell and V_{t3} – V_{t4} for the bottom cell) to be displaced from another by 180 degrees.

Patent Pending



(a)



(b)

Fig. 1 - (a) Single-phase Half-bridge Symmetrical Hybrid multilevel Inverter (IH1ϕ-HB-TC).
(b) Load voltage Waveform.

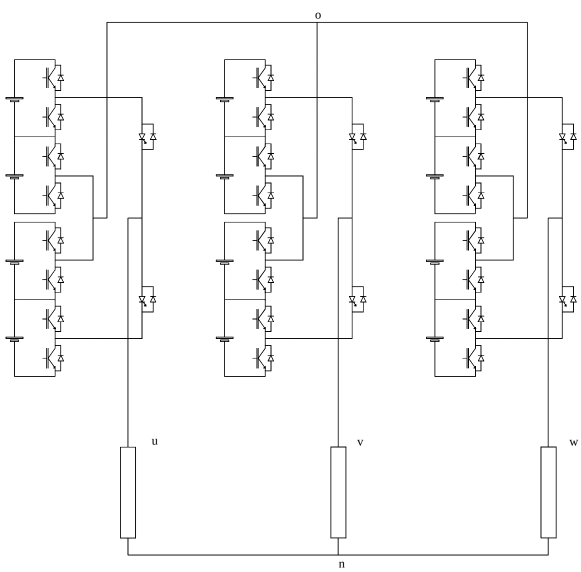
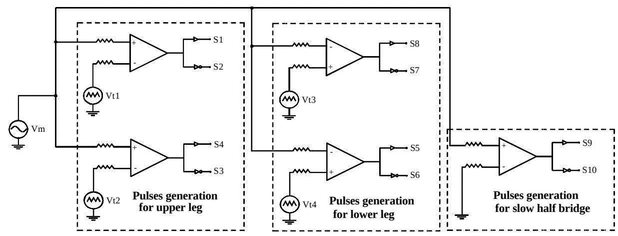


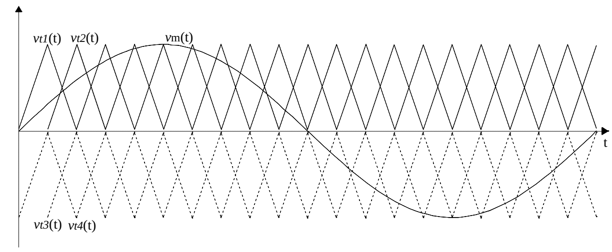
Fig. 2 - Circuit IH3ϕ-HB-TC, half-bridge configuration proposed.

To generate command signal for the slow switches, the modulating signal is compared with a zero level threshold. The signals generation scheme is shown in figure 3(a). Figure 3(b) presents the waveforms of the reference or modulating signal and the carrier signal, considering a low frequency of the carrier signals.

As illustrated in figure 3(b), the triangular signals for the superior cell are of a positive polarity, while the signals for the inferior cell are of a negative polarity.



(a)



(b)

Fig. 3 - (a) Switches command circuit of each inverter arm.
(b) Modulating signal and carrier.

2.2. Design Specifications

To verify the functioning principle IH3ϕ-HB-TC, with the modulation method already presented, a design example is done with the following specifications:

$E = 1.5KV$ $\quad P_o = 120KW$ $\quad f_0 = 50Hz$

$V_{f1} = 2KVrms$ $\quad \cos(f) = 0.8 \;\; ind.$ $\quad m_i = 0.94$

$R_o = 21.33\Omega$ $\quad L_o = 51mH$ $\quad f_s = 1600Hz$

Where:

P_o : Output Power

f_0 : Load Fundamental Frequency

V_{f1} : Fundamental effective phase voltage

$\cos(f)$: Load power factor

m_i : Modulation Index

R_o : Load equivalent resistance

L_o : Load equivalent inductance

f_s : Switching frequency

With the previously mentioned, the necessary parameters were defined for the simulation IH3ϕ-HB-TC.

2.3. Three-phase Half-bridge Symmetrical Hybrid Multilevel Inverter Simulations.

In this section it is possible to be observed the results obtained through digital simulation, with the design data previously pointed out, of the circuit in figure 2. For the circuit simulation is considered all the ideal components. The main waveshapes are shown in the following lines.

Figure 4 shows the waveform of the output phase voltage IH3ϕ-HB-TC in steady state. In this figure it is possible to appreciate that the level amount in the phase voltage is fifteen levels. Figure 5 shows the frequency spectrum of this voltage, where it is possible to observe that the high frequency components appear in lateral bands around multiple pairs of the switches commutation frequency.

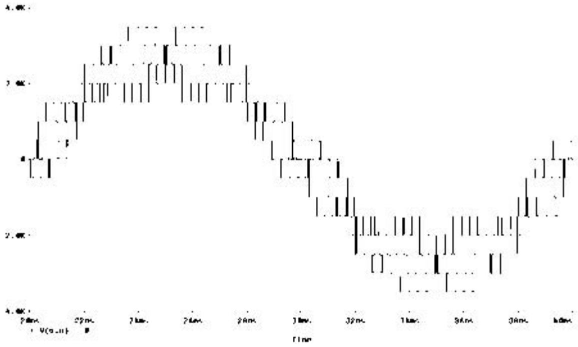


Fig. 4 - Load-phase voltage waveform of the inverter $v_{un}(t)$ in steady state.

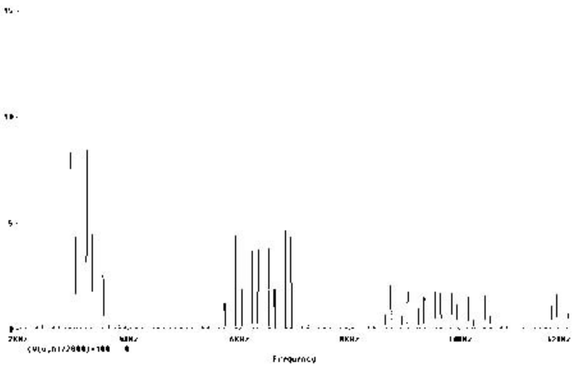


Fig. 5. Frequency spectrum of the load-phase voltage $v_{un}(t)$, in fundamental percentage.

The Fourier analysis for the three-phase inverter phase voltage yields a THD of 17.8 percent (Considering a great amount of harmonic (over 200) for the THD calculation). The highest load-phase voltage is 2800V.

The waveform of the line-to-line voltage in steady state is presented in figure 6. From the same figure it is possible to observe that the line-to-line voltage of the inverter has nine levels. The harmonic spectrum of the line to line voltage, in fundamental percentage is shown in Fig. 7, this figure shows that the frequency components have the same distribution that the one shown in figure 5. Therefore for this case the fact of having more levels does not mean that has a better waveform.

The Fourier analysis for the three-phase inverter line-to-line voltage is shown in table 2. As displayed, the THD of this voltage is 17.8 percent. The highest line-to-line voltage is 4850V. It is clear that the relation $v_{uv} = \sqrt{3} \cdot v_{un}$ is fulfilled for the inverter voltages.

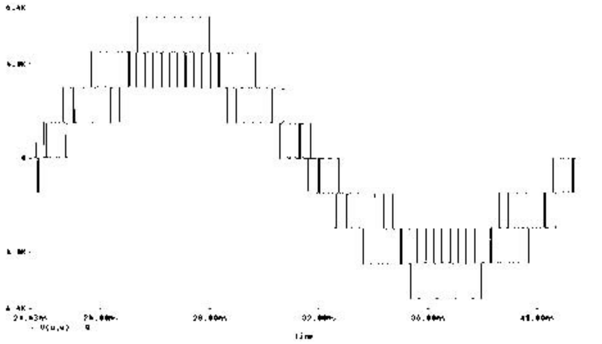


Fig. 6 - Waveform of the inverter line-to-line voltage $v_{uv}(t)$ in steady state.

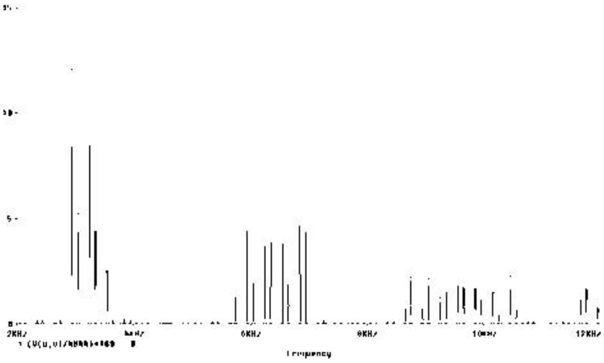


Fig. 7 - Line-to-line voltage spectrum of the three-phase inverter $v_{uv}(t)$, in fundamental percentage.

3. THREE-PHASE SYMMETRICAL HYBRID MULTILEVEL INVERTER, FULL-BRIDGE CONFIGURATION (IH3ϕ-FB-TC)

Reference [4] presents the circuit IH1ϕ-FB-TC, which is shown in figure 8 and 10.

The theoretical waveform for the circuit output voltage in figure 8 is shown in figure 9 where it is possible to appreciate that the output voltage $v_{ab}(t)$ has five levels. The numbers of levels in the load voltage is given by 2N+1, of the same form that H-Bridge multilevel inverters, and again N is the total of DC sources in the circuit.

If three IH1ϕ-FB-TC outputs are connected, in order that they feed a three-phase load in star disposition, then the outcome would be a three-phase symmetrical hybrid multilevel inverter, based on the full-bridge configuration (IH3ϕ-FB-TC), as shown in figure 10.

Each one of the modulating signals of the three-phase inverters is displaced in 120 degrees with regard to the other one.

The common point of the inverters will be called *'o'*, whereas the common point of the load star connection will be named *'n'*. The connection points between each single-phase inverter and the load will be called *'u'*, *'v'* and *'w'*.

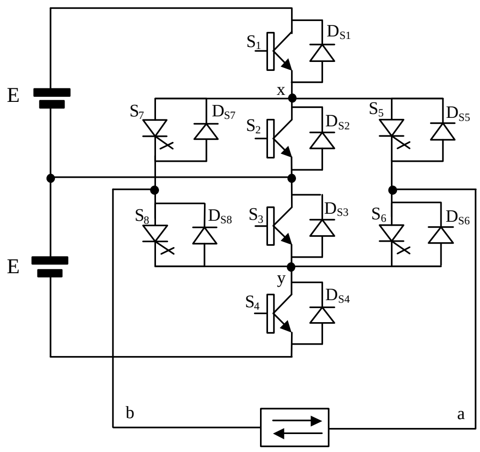


Fig. 8 – Single-phase symmetrical hybrid multilevel inverter based on the three-level cell (TC). Full-bridge configuration, IH1ϕ-FB-TC.

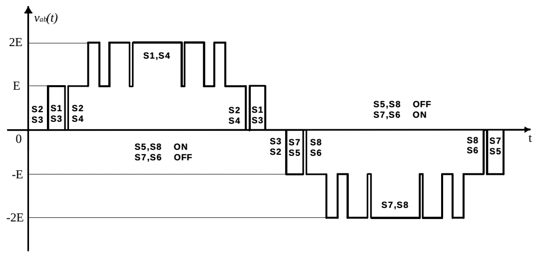


Fig. 9 - Output (Vab) voltage waveform.

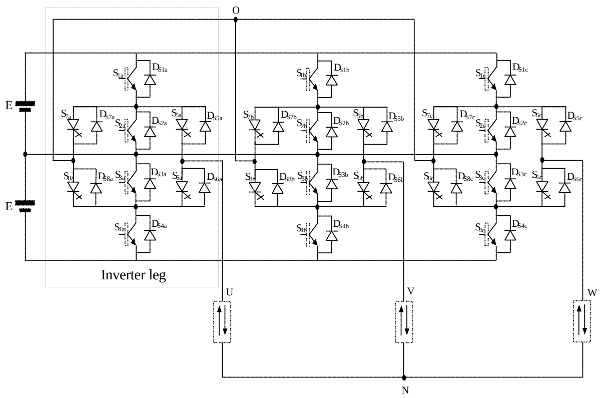


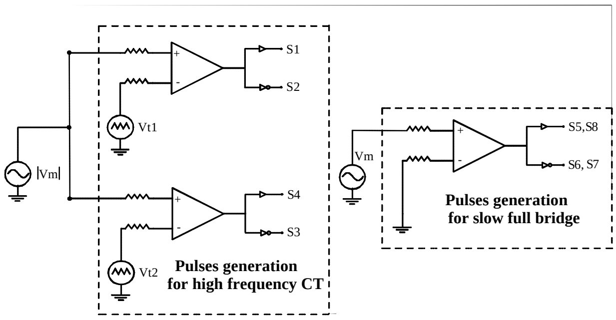
Fig. 10 - Proposed circuit IH3ϕ-FB-TC.

3.1. Modulation Strategy

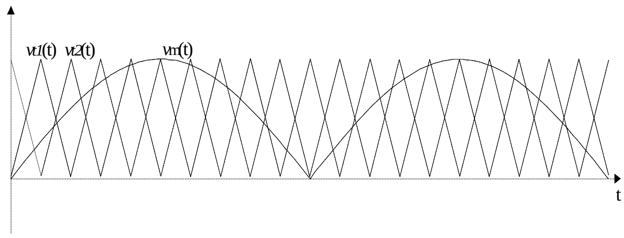
The modulation strategy is the same used for the single-phase inverter given in [4], with the exception that the references or modulating signals, as well as the carriers of each inverter leg, are out of phase in 120 degrees to each other. Also it requires that the carriers to be shifted from another by 180 degrees for each inverter cell as shown in Fig.11 (b).

3.2. Design specifications

The main scope of this paper is to obtain results in open loop modulation, and of these verify the distortion of voltages in the load, as well as the voltages level in the switches for two converters. Then to compares with the IH3ϕ-HB-TC behaves it is executed a design example using the same specification established in the previous section.



(a)



(b)

Fig. 11 - (a) Drive circuit for the IH3ϕ-FB-TC inverter. (b) Modulating signal and carrier signal for a leg of IH3ϕ-FB-TC.

3.3. Three-phase full-bridge symmetrical hybrid multilevel inverter simulations.

In this section will be observed the results obtained through digital simulation of the circuit in figure 10 with the design parameters given in section 2.2. For the circuit simulation is considered all the ideal components. The main waveshapes are shown next.

Figure 12 shows the waveform phase-load voltage for the IH3ϕ-FB-TC, in steady state. It is interesting to see in this figure that the amount of levels in the load phase voltage obtained with sinusoidal width pulse modulation has fifteen levels and line-to-line voltage are nine levels (Fig. 13).

The frequency spectrums of the load phase voltage as well as for line-to-line voltage of the IH3ϕ-FB-TC were identical to those obtained by IH3ϕ-HB-TC. Hence, the theoretical spectral analysis will be only one for each converter and is given in next section.

4. THEORETICAL FREQUENCY SPECTRUM OF THE OUTPUT VOLTAGES.

This section presents the study of the frequency spectrum and the total harmonic distortion (THD) for the phase and the line-to-line voltages of the topologies studied in the previous sections.

The equations obtained through Fourier analyses that define the output signals are given.

The calculation methodology of these equations is handed in [3].

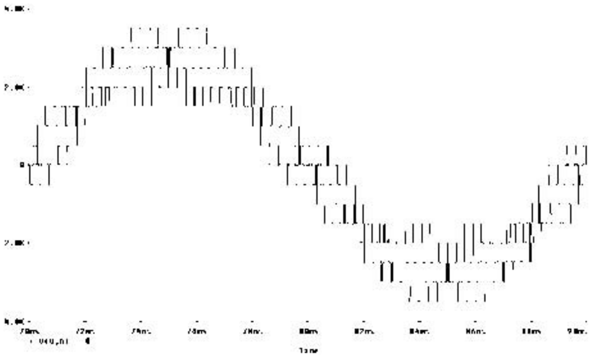


Fig. 12 - (a) The generated load-phase voltage waveforms $v_{un}(t)$ in steady state.

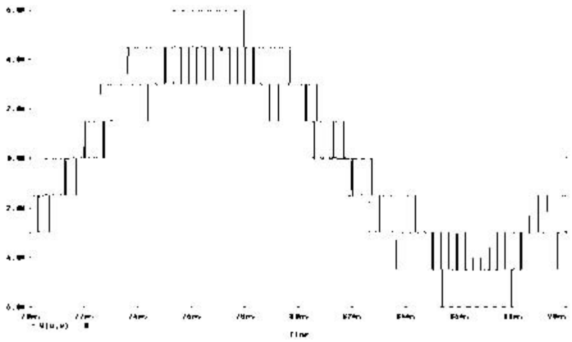


Fig. 13 - Waveform of the inverter line-to-line voltage $v_{uv}(t)$ in steady state.

The mathematical expression that defines the load-phase voltage of the three-phase topologies IH3ϕ-HB-TC and IH3ϕ-FB-TC is given by the equation (1):

$$v_{un}(t)=\begin{Bmatrix} 2E\,m_i\,sen(w_1 t) \\ +\sum\limits_{n,\,par}^{\infty}\sum\limits_{v,impar}^{\infty}\dfrac{4E}{3np}J_v(np\,m_i)\begin{Bmatrix} M_P\,sen(vw_1t+nw_st+q_P) \\ +M_N\,sen(vw_1t-nw_st+q_N)\end{Bmatrix}\end{Bmatrix} \tag{1}$$

Where $J_v(\cdot)$ represents the Bessel function of v order.

Like in the single-phase case, the harmonic components exist in lateral bands (vw_1) around multiple pairs of the commutation frequency (nw_s), situation observed in the simulations.

Figure 14 is a graph of the equation (1) normalized with regard to the 'E', for a 0.94 modulation index. The highest amplitude of the harmonic components of the phase inverter voltage and their frequencies are tabulated in table 1 and they are shown in function of the modulating index m_i, in figure 15.

On the other hand, the mathematical expression that defines the line-to-line voltage of the three-phase topologies IH3ϕ-HB-TC and IH3ϕ-FB-TC is given by equation 2: The harmonic components of the line-to-line voltage and the load-phase voltage have the same behaviour, just varying a little in amplitude and phase.

$$v_{uv}(t)=\begin{Bmatrix} 2\sqrt{3}\,E\,m_i\,sen\left(w_1t-\dfrac{p}{6}\right) \\ +\sum\limits_{n,\,par}^{\infty}\sum\limits_{v,impar}^{\infty}\dfrac{4E}{np}J_v(np\,m_i)\begin{Bmatrix} N_P\,sen(vw_1t+nw_st+a_P) \\ +N_N\,sen(vw_1t-nw_st+a_N)\end{Bmatrix}\end{Bmatrix} \tag{2}$$

The highest amplitude of the harmonic components of the line-to-line voltage and their frequency are tabulated in table 2 and they are displayed in function of the modulation index m_i in figure 17. Figure 16 is a graph of the normalized equation (2) with regard to 'E', for a 0.94 modulation index.

5. CONCLUSIONS

Two three-phase symmetrical hybrid approaches for multilevel inverters have been presented. The proposed circuits are the three-phase extensions of the topologies presented in [4]. Simulations were executed for these inverters feeding an inductive load and their switches were commanded through a simple sinusoidal-PWM modulation and unique pulse modulation, i.e., hybrid modulation characterization. The outcomes obtained from digital simulation for both inverters were made through a simple and well know PWM modulation only needing a sinusoidal reference unlike of that conventional one.

The waveforms of the load-phase voltage and the line-to-line voltage obtained were identical between both inverters. The waveform of the load-phase voltage has fifteen levels whereas the waveform of the line-to-line voltage has nine levels, besides both voltages have low harmonic distortion.

The main difference between the converters is evident, the full bridge converter needs less switches than the half bridge. However the switches of the IH3ϕ-FB-TC will undergo higher current stress, because, for a same power it will process more energy. The voltages across the fast switches are half of those obtained across the slow switches.

Finally, through the equations that define the load-phase voltage signals and the line-to-line voltage signals it was possible to corroborate that these ones (load-phase voltages and line-to-line voltages) characterize for having harmonic components in lateral bands around multiple pairs of the commutation frequency.

TABLE 1

Amplitude of the load-phase voltage harmonic components

Harmonic	**Amplitude**	**Frequency**
Fundamental A_1	$A_1=2E\,m_i$	w_1
Componentes $A_{n,v}$, $B_{n,v}$ n = 2,4,6... v = 1,3,5...	$A_{n,v}=\dfrac{4E}{3np}\left\|J_v(np\,m_i)\right\|M_P$ $B_{n,v}=\dfrac{4E}{3np}\left\|J_v(np\,m_i)\right\|M_N$	(vw_1+nw_s) (vw_1-nw_s)

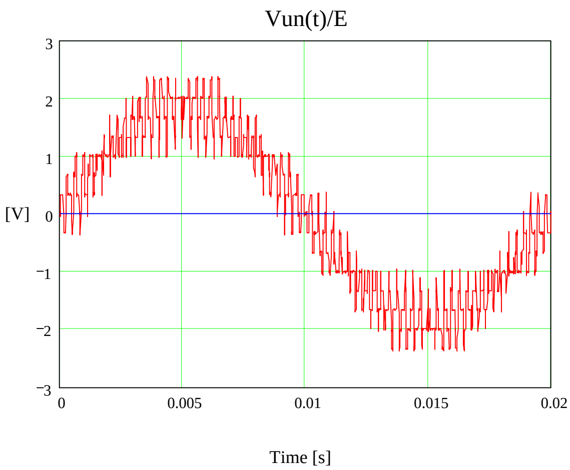


Fig. 14 - Graph of the equation (1) load-phase voltage, for n=100 and v=25.

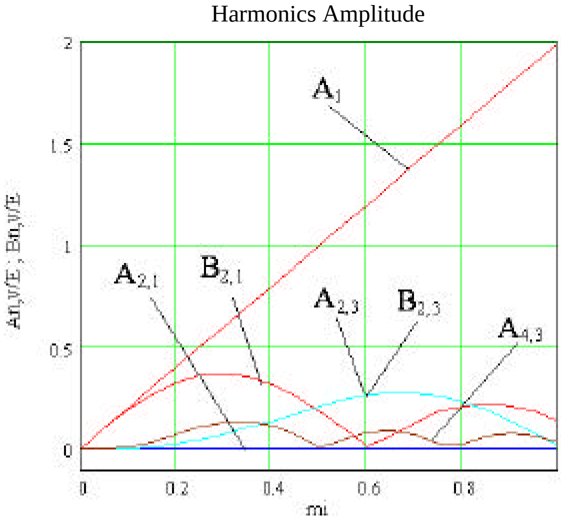


Fig. 15 - Amplitude of the harmonic components of the load-phase voltage IH3ϕ-HB-TC, IH3ϕ-FB-TC: A_1 = fundamental component, $A_{n,v}$ = harmonics to the frequency $(vw_1 + nw_s)$, $B_{n,v}$ = harmonics to the frequency $(vw_1 - nw_s)$; n = 2, 4, 6...; v = 1, 3, 5,...

6. REFERENCES

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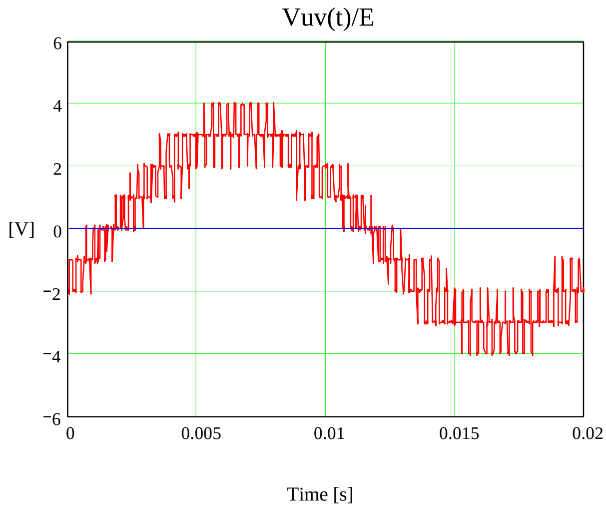

Fig. 16 - Graph of the equation (2) line-to-line voltage, for n=100 and v=25.

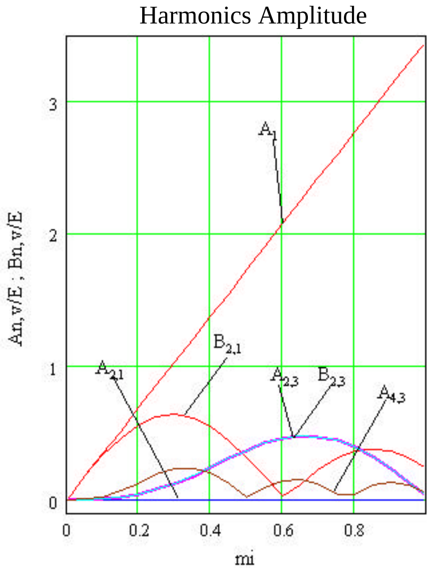

Fig. 17 - Amplitude of the harmonic components line-to-line voltage IH3ϕ-HB-TC, IH3ϕ-FB-TC: A_1 = fundamental component, $A_{n,v}$ = harmonics to the frequency $(vw_1 + nw_s)$, $B_{n,v}$ = harmonics to the frequency $(vw_1 - nw_s)$; n = 2, 4, 6...; v = 1, 3, 5,...

Table 2
Amplitude of the line-to-line voltage harmonic components

Harmonic	Amplitude	Frequency
Fundamental A_1	$A_1 = 2\sqrt{3}\,E\,m_i$	w_1
Componentes $A_{n,v}$, $B_{n,v}$ n = 2,4,6... v = 1,3,5...	$A_{n,v} = \frac{4E}{np}\lvert J_v(np\ m_i)\rvert N_P$ $B_{n,v} = \frac{4E}{np}\lvert J_v(np\ m_i)\rvert N_N$	$(vw_1 + nw_s)$ $(vw_1 - nw_s)$