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Comparison between Optimal Minimization of Total Harmonic Distortion and Harmonic Elimination with Voltage Control candidates for Multilevel Inverters

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This paper is devoted to the comparative evaluation of the two modulation strategies developed for multilevel inverters control: the harmonic elimination technique with voltage control (OHSW) and the optimal minimization of the total harmonic distortion method (OMTHD), which are a very important and efficient strategies of eliminating selected harmonics from spectrum of the output voltage or minimizing its total harmonic distortion in order to improve its quality. First, we describe briefly the basic idea and concept of each technique. Then, we present a study of the performances of each one by the means of a comparison between them. Simulation has also been presented to establish the effectiveness of the proposed analysis. Finally, we conclude with scope of further work.

Keywords: Multilevel Inverter (VSI), Cascade Inverter, Harmonic Elimination, Pulse Width Modulation (PWM), THD.

1. INTRODUCTION

Currently, the majority of the used electrical machine drives are three-phase AC systems. These drives operate with variable speed where the traction constitutes a good example. To use these drives with this operating mode, they should be equipped with variable frequency and voltage static converters.

Several variable speed architectures accompanying the AC machine drives exist. We will interest to the inverters. The first applications exploited the two-level structure. Because of the forwarded power current tendencies more and more important and the harmonics recommendations limits more and more severe, this structure cannot be used in many fields such as the traction and the power distribution systems. Thus, these fields require the use of structures known as “Multilevel” which comes to fill this gap and which are increasingly imposed. The merit to have created the first multilevel structure having the advantage of not using transformers, returns to A. NABAE and to its group in 1980 [1].

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The general function of these multilevel structures is to synthesize a desired AC waveform from several levels of DC voltages. Thus, they permit to overcome the voltage limitations of semiconductor devices in conventional two-level structure and to improve the quality of the output voltage waveform by reducing, for example, its Total Harmonic Distortion *THD* [1-7].

Numerous topologies have been founded in the published literature and widely used in many industrial applications, such as Static Var Compensators, HVDC link, variable speed drives and active filtering.

The Multilevel inverter using cascaded-inverters with separated DC sources, hereafter called a "*cascade multilevel inverter*" appears to be superior to other multilevel structures in terms of its structure that is not only simple and modular but also requires the least number of components [6]. This modular structure makes it easily extensible for higher number of desired output voltage levels without undue increase in circuit power complexity. In addition, extra clamping diodes or voltage balancing capacitor are not necessary.

For controlling this multilevel structure (or other types of multilevel topologies), many modulation strategies are very effective and more interesting. These strategies are generally derived from those of two-level structure control. They can be classified according to switching frequency into two groups, the strategies of the first group work with low switching frequencies and those of the second one work with high switching frequencies. The most popular are:

- The Sub-harmonic pulse widths modulation methods also called Sinusoidal PWM or sine-triangle PWM;
- The Pre-calculated modulation methods;
- The Space Vector modulation (SVM) methods,
- The Sigma Delta modulation (SDM) methods;
- The Hybrid modulation strategies which combine two or more methods.

This paper focuses on two alternatives of pre-calculated techniques (belong to the first group): the general harmonic elimination technique with voltage control and the optimal minimization of the total harmonic distortion method. They will be applied to the cascade multilevel inverter. The purpose of this study is to confronting, by a comparison between them, these two techniques studied in our previous works [8-12]. The question is to know whether the first or the second method is the best modulation control ? and to know, initially, if there are great differences between theme. The comparison will be presented in several aspects. The difference will be especially evaluated in term of total harmonic distortion *THD*. For that, we will propose to quantify the harmonics present in the multilevel inverter output voltages.

To achieve the assigned aim, the paper is divided into many sections. After this introducing one, a brief description of the cascade multilevel inverter will be first provided, followed by the fundamental switching scheme used for its control. This switching scheme produces a staircase waveform and involves many control options in order to approach desired sinusoid. It consists respectively to reduce or eliminate some of the lowest unwanted harmonics by determining the best switching angles where the switches will operate.

The comparison between two control options mentioned above and simulation results will then be done. Finally, a summary of various results and some conclusions will be presented and suggestions of our possible future research in the area of multilevel inverter control will also noted in the concluding section.

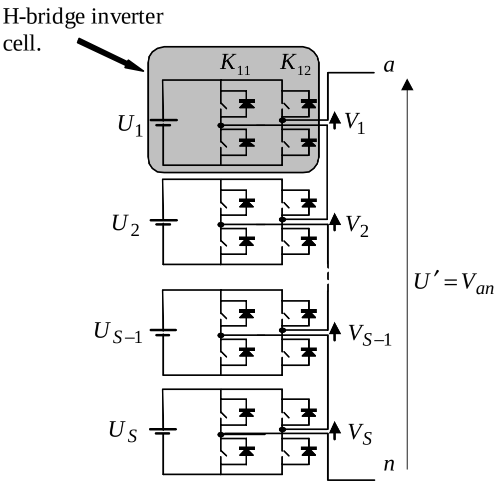

Fig. 1 The single-phase structure of the cascade multilevel inverter

2. CASCADE MULTILEVEL INVERTER- STRUCTURE AND OUTPUT VOLTAGE WAVEFORM

Figure 1 shows the single-phase structure of a cascade multilevel inverter. It consists of a series of H-bridge (single-phase full-bridge) inverter cells. Each inverter cell can generate, for the output voltage V_i ($i = 1, 2, \cdots, S$ with S number of cells employed) three different values (levels), $+U_i$, 0 et $-U_i$ by connecting the DC source U_i to the AC output side by different combinations of the four devices [13-15]. Noting in this level that the voltages U_i of the DC sources supplied inverter cells may be different. So, they can or can not be equal.

The output voltage V_i can be expressed as :

$$V_i = U_i\left(f_{i1} - f_{i2}\right) \tag{1}$$

where f_{i1}, f_{i2} are, respectively, the connection or switching functions of the upper switches (K_{i1}, K_{i2}) of each cell, which define its states (switch on or off).

The AC output voltage V_{an} (U') is, therefore, the sum of all the individual inverter outputs:

$$V_{an} = V_1 + V_2 + \cdots + V_S = \sum_{i=1}^{S} V_i \tag{2}$$

Using the connection functions, equation (2) becomes:

$$V_{an} = U_1(f_{11} - f_{12}) + \cdots + U_S(f_{S1} - f_{S2}) \tag{3}$$

For the three-phase system, the output of three identical structure of single-phase cascaded inverter can be connected in either wye or delta configuration.

In this case, line voltage can be expressed in term of two phase voltages. For example, the line voltage V_{ab} is the potential between phase *a* and phase *b* which can be expressed as :

$$V_{ab} = V_{an} - V_{bn} \tag{4}$$

The maximum number of the phase voltage levels can achieved 3^S , where S is the number of cells or H-bridges used.

Fig. 2 illustrates one of the more possible low frequency switching scheme of the output voltage waveforms that can be synthesized by the cascaded multilevel inverter of fig. 1. This switching scheme is designed as a fundamental switching scheme producing a staircase waveform U' to approximate the desired sinusoid. It represents the typical or generalized multilevel output voltage waveform involving pre-calculated or predetermined switching angles modulation methods. This work is centred on this waveform chosen here for the study. It is a periodic waveform which presents the odd half and quarter-wave symmetric characteristic. It contains $4S$ switching angles namely $\alpha_1, \alpha_2, \cdots, \alpha_S$ per cycle (period) and structured by several voltage levels which are equal or not.

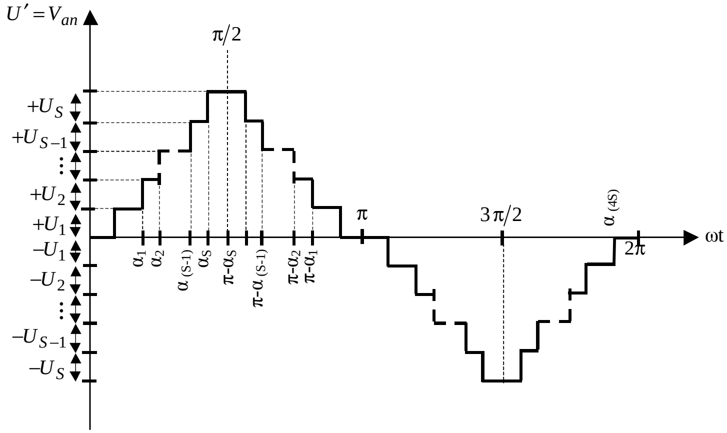

Fig. 2 Chosen Generalized multilevel output voltage waveform (fundamental switching scheme).

3. REVIEW OF OPTIMIZATION GENERALIZED MULTILEVEL WAVEFORM TECHNIQUES

According to the choice of generalized waveform parameters, there are three possible optimization techniques for reducing the total harmonic distortion (*THD*) of the output voltage inverter:

- The optimization technique based on the step amplitudes (step heights). In this case, we use a generalized waveform with equally width or equally spaced steps (i.e. with constant distance between switching angles) and varied step heights (Fig.3). To be obtained, this generalized waveform requires a variable DC supply voltage.

- The optimization technique based on the step spaces (switching angles). For this case, the used generalized waveform (Fig.4) is known as "*a regular staircase waveform*" with equal height steps (equal amplitudes) and variable widths (variable step spaces). This requires a constant DC supply voltage ($U_1 = U_2 = \cdots = U_S = U$).

- The optimization technique based on both width and height steps which are variable in this case. This concern an arbitrary generalized waveform (Fig. 5). Similar to the generalized waveform used in the first technique, this one need also a variable DC supply.

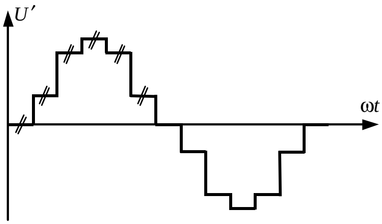

Fig. 3 A generalized waveform with equally width steps (variable DC supply voltage).

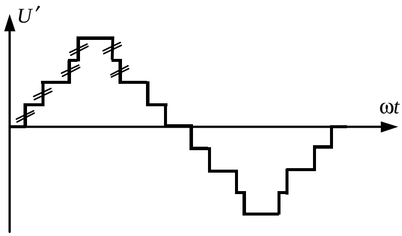

Fig. 4 A regular staircase generalized waveform (constant DC supply voltage)

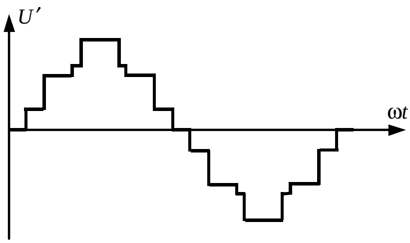

Fig. 5 An arbitrary generalized waveform (variable DC supply voltage)

4. GENERALIZED MULTILEVEL VOLTAGE WAVEFORM QUALITY IMPROVEMENT APPROACHES

Once the optimization technique of the generalized waveform has been chosen, one can derive some control approaches to improve its quality. The main approaches are :

- The Harmonic Elimination approach, for which the switching angles are chosen to eliminate a certain number of selected (generally the lowest unwanted) harmonics. This results in waveform *THD* reduction [8, 9];

- The optimal Minimization approach, for which the switching angles are determined to minimize, the most effectively possible, the waveform *THD*. This reduces, generally, the rate of each harmonic, without eliminating it inevitably [10-12].

These two approaches which will be briefly defined in the following sections will be applied in this study, for reasons of simplicity, to the regular staircase generalized waveform.

5. HARMONIC ELIMINATION (*OHSW*) APPROACH

The general harmonic elimination technique for multilevel inverter is referred in the literature to as “Optimized Harmonic Stepped Waveform *OHSW*”. Its objective is to reduce the total harmonic distortion (*THD*) in the output voltage. The basic concept of this reduction is to eliminate specific harmonics, which are generally the lowest orders, with an appropriate choice of switching angles. This is realised by adapting, skilfully, the idea of the Selective Harmonic Eliminated PWM (*SHE PWM*) for 3-level inverter control based on the unipolar PWM switching scheme [16] to a generalized multilevel waveform synthesized from several level of DC voltages.

Because of the symmetries of the chosen generalized waveform shown in Fig. 2, only the odd harmonics exist. For this reason, its Fourier coefficients, which are calculated as the simple sum of the coefficients of all its rectangular waves, are given by the following equation:

$$a_n = \frac{4}{n\pi}\sum_{k=1}^{S} U_k \cos(n\alpha_k) \tag{5}$$

Assuming a regular staircase waveform ($U_1 = U_2 = \cdots = U_S = U$), this equation becomes:

$$a_n = \frac{4U}{n\pi}\sum_{k=1}^{S} \cos(n\alpha_k) \tag{6}$$

where U is the voltage amplitude of the DC source (DC supply voltage); n is an odd harmonic order; S is the number of DC sources or H-bridge cells; α_k are the optimized harmonic switching angles per quarter cycle.

Evidently, these angles must, constantly, satisfy the basic constraint:

$$\alpha_1 < \alpha_2 < \alpha_3 < \cdots < \alpha_S < \frac{\pi}{2} \tag{7}$$

The Amplitude of any harmonic can be obtained by setting equation (6), with respect harmonic, equal to pre-specified value. But based on the performance criteria, this equation can be solved for *S* variables, α_1 to α_S, by:

- Either, equating *S* predominant lower frequency harmonics to zero in order to cancel it.
- Or provide for voltage control with simultaneous harmonics elimination, i.e. equating (*S*-1) lower-order harmonics to zero and assigning a specific value to the fundamental component. This approach is the approach proposed and investigated in this paper.

Basically, the lowest odd harmonic components should be removed from a single-phase system, whereas in the three-phase system, they are the lowest non-triplen harmonic components that need to be eliminated. Thus, to eliminate *S*-1 harmonics from the output voltage inverter, *S* switching angles need to be known. It implies, mathematically, that *S* equations formed from equation (6) are necessary. These equations, after some calculations, can be written as:

For the single-phase system:

$$\begin{aligned} &\cos(\alpha_1)+\cos(\alpha_2)+\ldots+\cos(\alpha_S)=\frac{SM\pi}{4} \\ &\cos(3\alpha_1)+\cos(3\alpha_2)+\ldots+\cos(3\alpha_S)=0 \\ &\vdots \\ &\cos(n\alpha_1)+\cos(n\alpha_2)+\ldots+\cos(n\alpha_S)=0 \end{aligned} \tag{8}$$

For the three-phase system:

$$\begin{aligned} &\cos(\alpha_1)+\cos(\alpha_2)+\ldots+\cos(\alpha_S)=\frac{SM\pi}{4} \\ &\cos(5\alpha_1)+\cos(5\alpha_2)+\ldots+\cos(5\alpha_S)=0 \\ &\vdots \\ &\cos(n\alpha_1)+\cos(n\alpha_2)+\ldots+\cos(n\alpha_S)=0 \end{aligned} \tag{9}$$

where n is an odd number for the single-phase system, different from three and its multiples for the three-phase system; $M=\frac{h_1}{SU}$ is the modulation index and h_1 is the amplitude of the fundamental component.

The resolution of these two systems, which are nonlinear, is achieves by the algorithm of Newton-Raphson method (uses in this paper) or by any other iterative method of nonlinear systems resolution [8, 9].

6. OPTIMAL MINIMIZATION OF TOTAL HARMONIC DISTORTION

The basic idea for such a method, developed in our laboratory [10-12] and confirmed by recent work of [17], is to adjust and calculate switching angles in order to minimize the output voltage *THD*. To minimize the *THD*, it is necessary that its partial derivative with respect to each switching angle equal zero. It is implied that the derivative partial of its square is also set to be zero (*THD* is positive).

After development and some simplifications, the *THD* of the chosen multilevel generalized waveform (periodic with odd quarter-wave symmetric characteristic) depicted in Fig.2 is given by this general formula:

$$THD = \sqrt{\left[\frac{\pi^2}{8}\times\frac{\left(\sum_{k=1}^{S}U_k\right)^2-\frac{2}{\pi}\left[\alpha_1U_1^2+\sum_{j=2}^{S}\alpha_j\left(U_j^2+2U_j\sum_{i=1}^{j-1}U_i\right)\right]}{\left(\sum_{k=1}^{S}U_k\cos\alpha_k\right)^2}\right]-1} \qquad (10)$$

See [11-12] for proof of this expression.

Suppose the step of equal heights (regular staircase waveform $: U_1 = U_2 = \cdots = U_S = U$). Then the *THD* is given by:

$$THD = \sqrt{\left[\frac{\pi^2}{8}\times\frac{\left(S^2-\frac{2}{\pi}\sum_{k=1}^{S}(2k-1)\quad\alpha_k\right)}{\left(\sum_{k=1}^{S}\cos\alpha_k\right)^2}\right]-1} \qquad (11)$$

What implies:

$$THD^2 = \left[\frac{\pi^2}{8}\times\frac{\left(S^2-\frac{2}{\pi}\sum_{k=1}^{S}(2k-1)\quad\alpha_k\right)}{\left(\sum_{k=1}^{S}Cos(\alpha_k)\right)^2}\right]-1 \qquad (12)$$

Differentiating this latest equation to determine the partial derivatives and set these partial derivatives equal to zero, we obtains this general expression:

$$\frac{\partial\ \left(THD^2\right)}{\partial\ \ (\alpha_C)} = 0$$

$$(2C-1)\sum_{k=1}^{S}\cos(\alpha_k)+\left[2\sum_{k=1}^{S}(2k-1)\alpha_k-\pi S^2\right]\sin(\alpha_C)=0 \quad (13)$$

where $C = 1, \quad 2, \quad \cdots, \quad S$

Thus, to minimize the output voltage *THD* of the generalized multilevel waveform, S switching angles ($\alpha_1, \ \alpha_2, \ \cdots, \ \alpha_S$) determined over one-quarter-cycle, need to be known, whereas and similar to the first approach the other angles (from α_{S+1} until α_{4S}) result directly by symmetry (see Fig. 2). These S switching angles must, also, satisfy the condition (7). To obtain these angles, a system with S equations formed from (13) is necessary. This system is nonlinear. Its resolution is done by the Newton-Raphson method.

7. COMPARISON BETWEEN "*OMTHD*" AND "*OHSW*" TECHNIQUES

To analyze the harmonic performance of the two techniques for purpose of comparison, several harmonic measures are possible. The total harmonic distortion *THD* is one of these measures. It's the popular performance index for power converters. It evaluates the quantity of harmonics contents in the output waveforms.

To calculate the values of the *THD* (chosen as basic performance criteria in this study), MATLAB is used as simulating tool.

7.1 Simulations Results

Some analytical results giving the appropriated switching angles can be obtained by using and running our programs. For instance, the values of switching angles (in degrees) to

- optimize the *THD* of a five-level generalized waveform are: $\alpha_1 = 13.7610$, $\alpha_2 = 44.8428$.
- eliminate the third order harmonic from a five-level generalized waveform and control its fundamental component are : $\alpha_1 = 15.9562$, $\alpha_2 = 44.0438$.

The output voltage *THD* values of this waveform and for the generalized waveform with any different levels are obtained by substituting the switching angle values into equation (11).

In order to compare the two modulation strategies, the *THD* values have been compared under the same condition (*M* constant). Therefore, we start, for the various switching angles founded, with the calculation of the output voltages *THD* of many cascaded inverters (different levels) controlled by the *OMTHD* technique. Then, deduce from these switching angles the modulation index values imposed by diverse founded solutions. After that, we will calculate the output voltages *THD* of these same inverters but now controlled by the *OHSW* technique and which correspond to the modulation index values imposed by the first technique. The results obtained, as function of the number of switching angles, are tabulated for the *OMTHD* technique in summary table 1 and for the *OHSW* technique in summary table 2.

Table 1. Output Voltage *THD* as function of the number of switching angles for the *OMTHD* technique

Number of switching angles per quarter-cycle	THD % *OMTHD*
$S = 2$	16,70
$S = 3$	11,58
$S = 4$	08,89
$S = 5$	07,21

Table 2. Output Voltage *THD* as function of the number of switching angles for the *OHSW* technique.

Number of switching angles per quarter-cycle	THD % *OHSW*
$S = 2$	17,00
$S = 3$	14,32
$S = 4$	09,70
$S = 5$	08,19

These two summary tables show, for the two modulation techniques, that more the number of switching angles (i.e. the number of inverter levels) increases, more the output voltage *THD* decreases and the approximation of this voltage to a sinusoidal waveform will get better and better. Moreover, the founded values express the improvement obtained with the *OMTHD* technique comparatively to the *OHSW* method owing to the fact that the *THD* is considerably reduced. Table 3 specifies, for some switching angles, the rate of this reduction.

From this last table, it is preferable for minimizing the output voltage *THD* of multilevel inverters to privilege the *OMTHD* technique over the *OHSW* one. Nevertheless, the *THD* is not enough because it doesn’t constitute the only comparison criterion. The results must be confronted with those concerning the remaining harmonics (especially the lowest).

Table 3. Rate of reduction obtained in term of *THD* by the *OMTHD* compared to *OHSW*

Number of switching angles per quarter-cycle	*Reduction obtained (%)*
$S = 2$	01,76
$S = 3$	19,13
$S = 4$	08,35
$S = 5$	11,97

The advantage of the improvement obtained with the *OMTHD* in term of the total harmonic distortion, is unfortunately obtained to the detriment of the lowest harmonics disappearance which are eliminated by the *OHSW* technique. To explain this, the model of the five-level cascade inverter with two-separated DC sources and two H-bridge cells (two switching angles per quarter-cycle) constructed in MATLAB-Simulink-Power System software is used for the simulation. This inverter is chosen to generate the same generalized waveform (five-level generalized waveform) cited above as an example for programming.

The principal characteristics of this simulated inverter are:

- The total DC supply voltage is 400V. Thus, the amplitude supplied each H-bridge cell is set to be 200V;
- The operating frequency is 50Hz.

The results are shown in Fig.6 and Fig. 7. They present frequency spectrums of its output voltage waveforms.

The examination of the two frequency spectrums obtained shows clearly that:

- The third harmonic eliminated by the *OHSW* technique, have reduced amplitude with *OMTHD* one.

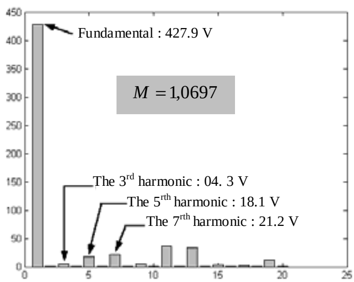

Fig. 6 Frequency spectrum of the output voltage of the five-level cascade inverter controlled by *OMTHD* technique

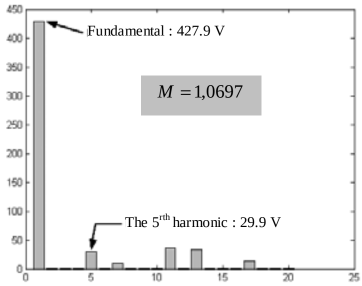

Fig. 7 Frequency spectrum of the output voltage of the five-level cascade inverter controlled by *OHSW* technique.

The fifth harmonic which is the first harmonic remaining in the output voltage frequency spectrum of the inverter controlled by *OHSW*, present reduced amplitude when we control the inverter by the *OMTHD*.
In order to generalize the study and verifying the theoretical results, other computer simulations are elaborated. From these simulations, it may be noticed that:

- The lowest harmonics eliminated by the *OHSW* technique have increasingly reduced amplitudes with the increase in the number of switching angles per quarter-cycle if the inverter is controlled by *OMTHD* method. The calculation of these amplitudes confirms that, these harmonics have relative amplitudes lower than 3 % of the fundamental one. By more increasing the number of switching angles (increasing the output voltage inverter levels), these harmonics become increasingly negligible and approaching zero.
- The amplitude of the first uncancelled harmonic remaining in the output voltage frequency spectrum of the inverter with the *OHSW* technique is higher then that of the same harmonic obtained with the *OMTHD*.

The simulation results validate the theoretical results quite well. Both results indicate that the *OMTHD* technique is capable of rendering good harmonic performance, especially in term of *THD*, in the output voltage inverter more than the *OHSW*. However, as mentioned in [10-12], the main drawback of using this new technique with the proposed manner is that the fundamental component can not be controlled (constant modulation index).

8. CONCLUSION

If the minimum harmonic content in the output voltage is a main concern, the paper revealed the superiority of Optimal Minimization of the Total Harmonic

Distortion *OMTHD* technique over Optimized Harmonic Stepped-Waveform *OHSW* method. The study carried out, based in the comparison between the two modulation techniques, shows that the *OMTHD* approach is preferred and particularly interesting. It appeared very useful since it makes possible to act on the total harmonic distortion with an increased precision as well as the number of levels increases. Therefore the resulting staircase output voltage which has the minimum harmonic content approaches a desired sinusoidal waveform.

The advantage of the improvement obtained in term of the total harmonic distortion, is unfortunately obtained to the detriment of the lowest harmonics disappearance. In spite of their presences, these harmonics present a very low amplitudes (<3 % of the fundamental amplitude), especially with the increase in the output voltage levels, i.e. with the increase in the switching angles number. Indeed, if this number is sufficiently great, it is possible to consider these harmonics as negligible. So, this point constitutes a negligible comparison criterion.

Despite all these advantages, the *OMTHD* with the proposed manner suffer, comparatively to the *OHSW*, from impossibility to control the fundamental component of the output voltage. It represents its great drawback.

This control voltage problem motivate us to try to propose in future researches other law control (other control approaches) derived directly from this new modulation technique and allowing to overcome such problem. The idea is to determine, for each modulation index value, the switching angles able to minimize, as well as possible, the total harmonic distortion.

A second suggestion for our researches would be to extend this study to the others generalized waveforms in order to locate, once again, the advantages and the performances of this new approach.

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